The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2022-5

Workshop on Theoretical Ecology and Global Change

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Non-linear Ecosystem Responses

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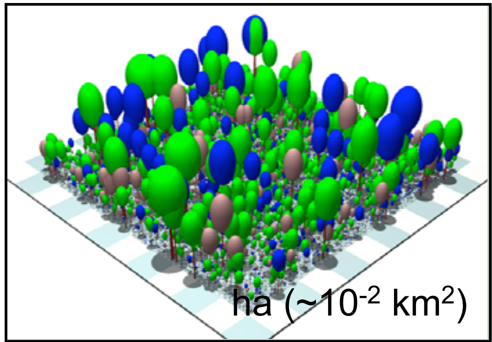
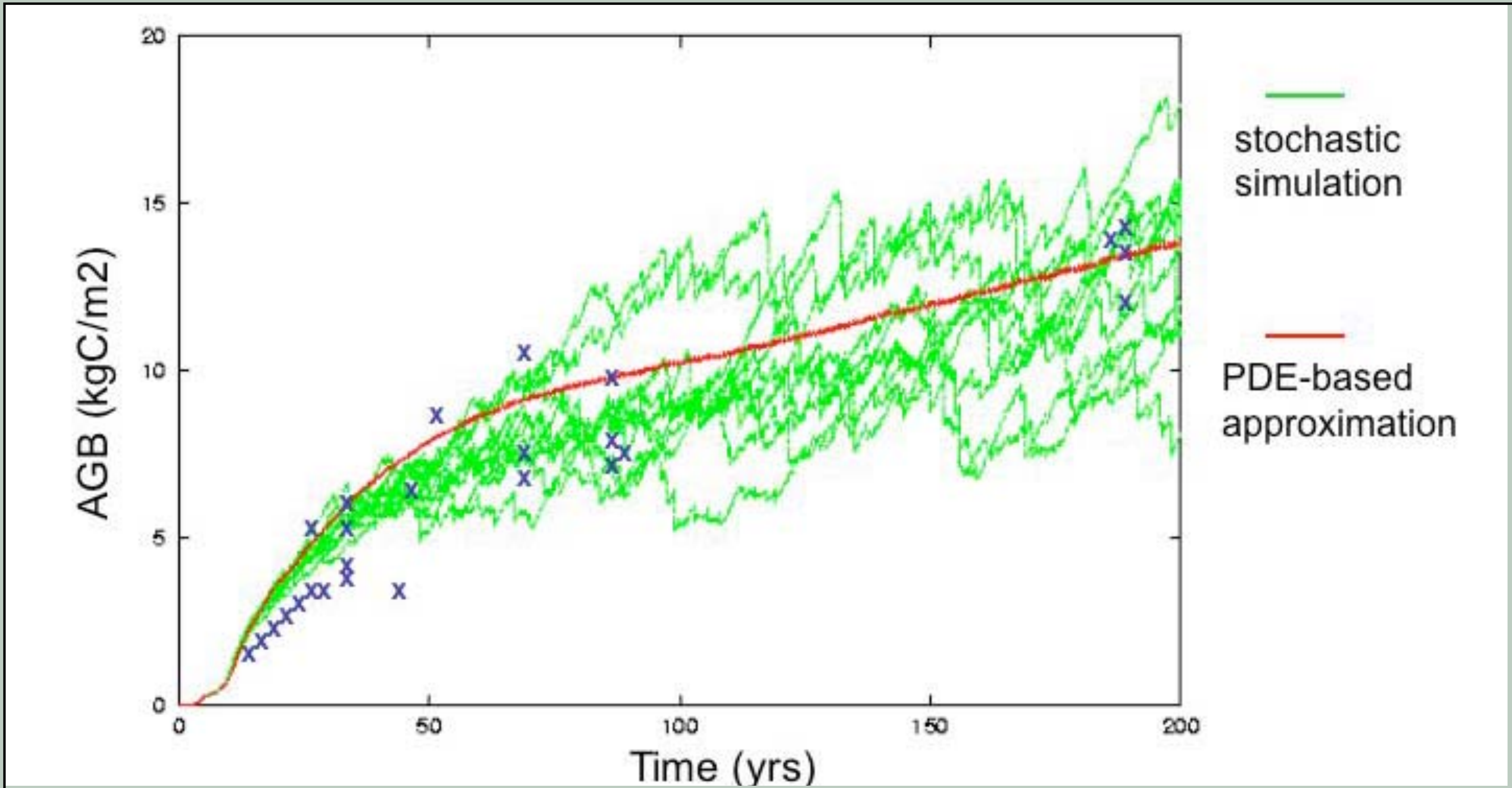


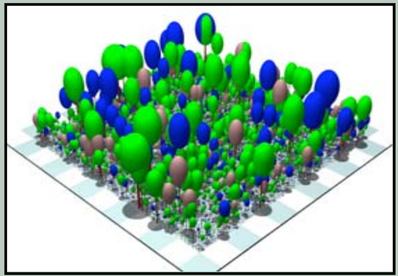
(Moorcroft et al. 2001)

ED dynamics at San Carlos Tropical forest (2^{o}N,68^{o}W): trajectory of above-ground biomass:



- accurately captures the behavior of corresponding individual-based model by tracking the dynamic horizontal & vertical sub-grid scale heterogeneity in canopy structure.

(Moorcroft et al. 2001)



A size & age-structured terrestrial biosphere model

PDE:
$$\underbrace{\frac{\partial n^{(i)}(z,a,t)}{\partial t}}_{\text{ch. in density of plant type } i} = \underbrace{-\frac{\partial}{\partial z}\left[g(z,a,t)n^{(i)}(z,a,t)\right]}_{\text{growth}} \underbrace{-\frac{\partial}{\partial a}n^{(i)}(z,a,t)}_{\text{aging}} \underbrace{-\mu(z,a,t)n^{(i)}(z,a,t)}_{\text{mortality}}$$

PDE:
$$\underbrace{\frac{\partial p(a,t)}{\partial t}}_{\text{ch. landscape age distribution}} = \underbrace{-\frac{\partial}{\partial a}p(a,t)}_{\text{aging}} \underbrace{-\lambda(a,t)p(a,t)}_{\text{disturbance}}$$

BC: $n(z_0,t) = \dfrac{1}{g(z_0,t)}\displaystyle\int_0^\infty f(z,t)n(z,t)\,dz$

BC: $p(0,t) = \displaystyle\int_0^\infty \lambda(a,t)n(a,t)\,da$

BC: $n^{(i)}(z,0,t) = s(z,a,t)\displaystyle\int_0^\infty s(z,a,t)\,n^{(i)}(z,a,t)\,da$

(Moorcroft et al. 2001, Moorcroft 2006)

Conclusions

In contrast to traditional 'big-leaf' biosphere models, structured biosphere models such as ED scale formally between fast timescale plant-level physiological responses to climate, and long-term large-scale ecosystem dynamics.

Enables them to:

- have both realistic short-term and long-term vegetation dynamics.

- incorporate the effects of natural and anthropogenic disturbances (wind-throw fire, land clearing, land abandonment, forest harvesting etc.) on ecosystem composition, structure & function.

- ability to connect to measurements

Forms of disturbance

Treefall Gap Malaysia

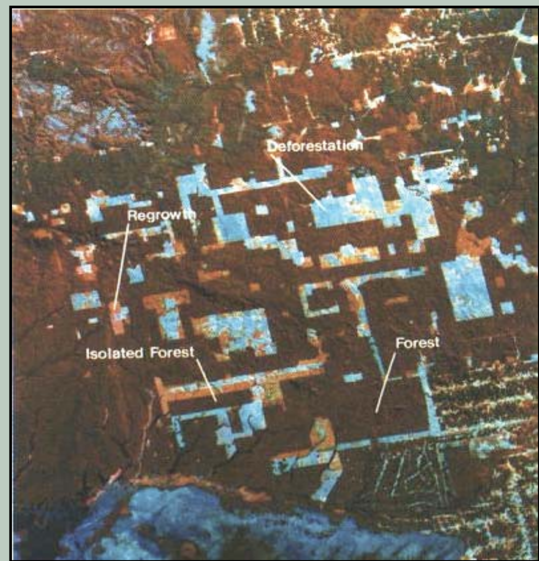
Land-slip Malaysia

Fires in Amazonia

Forest Pathogens Alaska

Shifting Agriculture Venezuela

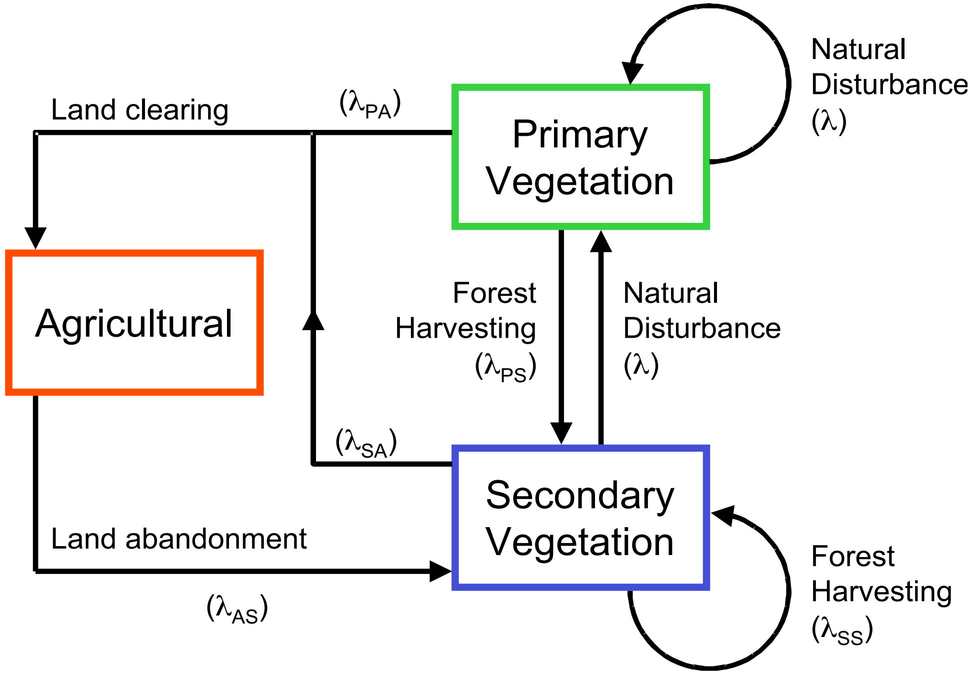
Land-Use Change Rondonia



Albani et al. 2006

Incorporating land-use change

$$\underbrace{\frac{\partial}{\partial t}\underline{p}(a,t)}_{\text{ch. in land class \& age distribution}} = -\underbrace{\frac{\partial}{\partial a}\underline{p}(a,t)}_{\text{aging}} - \underbrace{\mathbf{\Lambda}(a,t)\underline{p}(a,t)}_{\text{disturbance}},$$



$$\underline{p}(a,t) = [p_1(a), p_j(a), \ldots p_m \;]$$

$$\mathbf{\Lambda}(a,t) = \begin{pmatrix} \lambda & \lambda & 0 \\ \lambda_{PS} & \lambda_{SS} & \lambda_{AS} \\ \lambda_{PA} & \lambda_{SA} & 0 \end{pmatrix}$$

$$\underbrace{\underline{p}(0,t) = \sum_{j=1}^{n_{dist}} \int_0^{\infty} \lambda(a,t)p_j(a,t)da.}_{\text{formation of newly disturbed areas}}$$

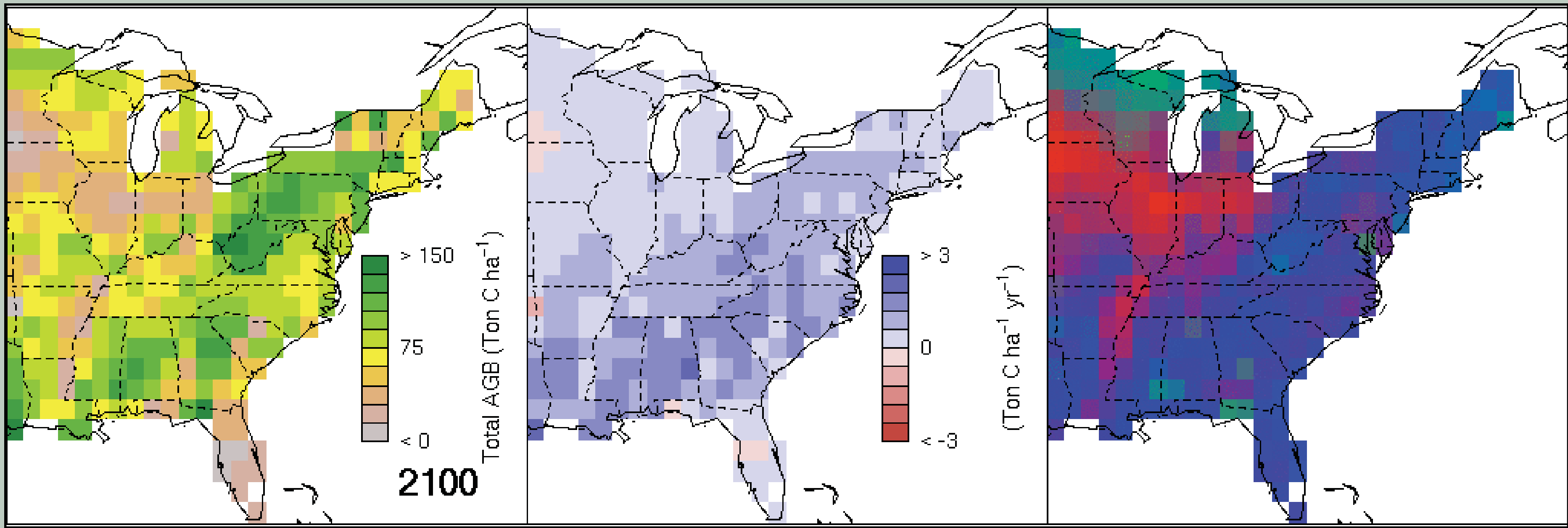
historical fraction of agricultural land in each county 1800-2100

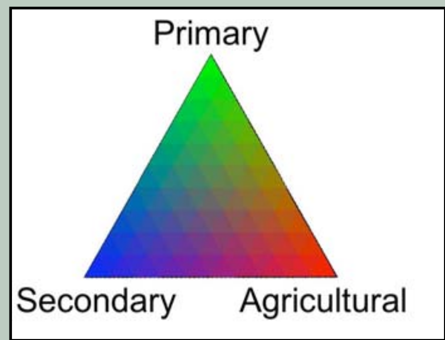
regional historical patterns of forest harvesting (USFS)

Albani et al. 2006

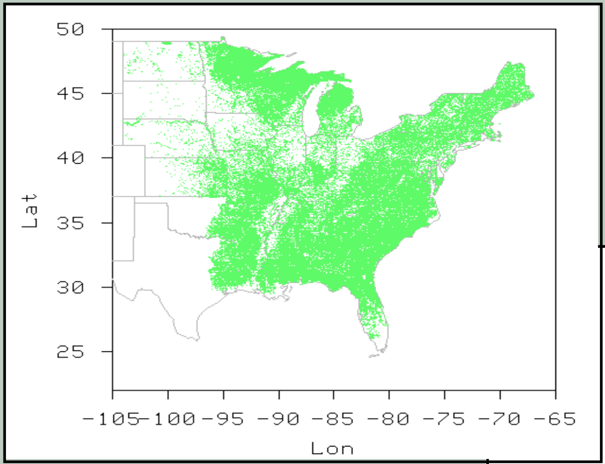
ED model: predicted impacts of land-use history on the carbon dynamics of the Eastern US

above gnd. biomass (tC ha^{-1}) carbon uptake (NEP, tC ha^{-1} y^{-1}) land use

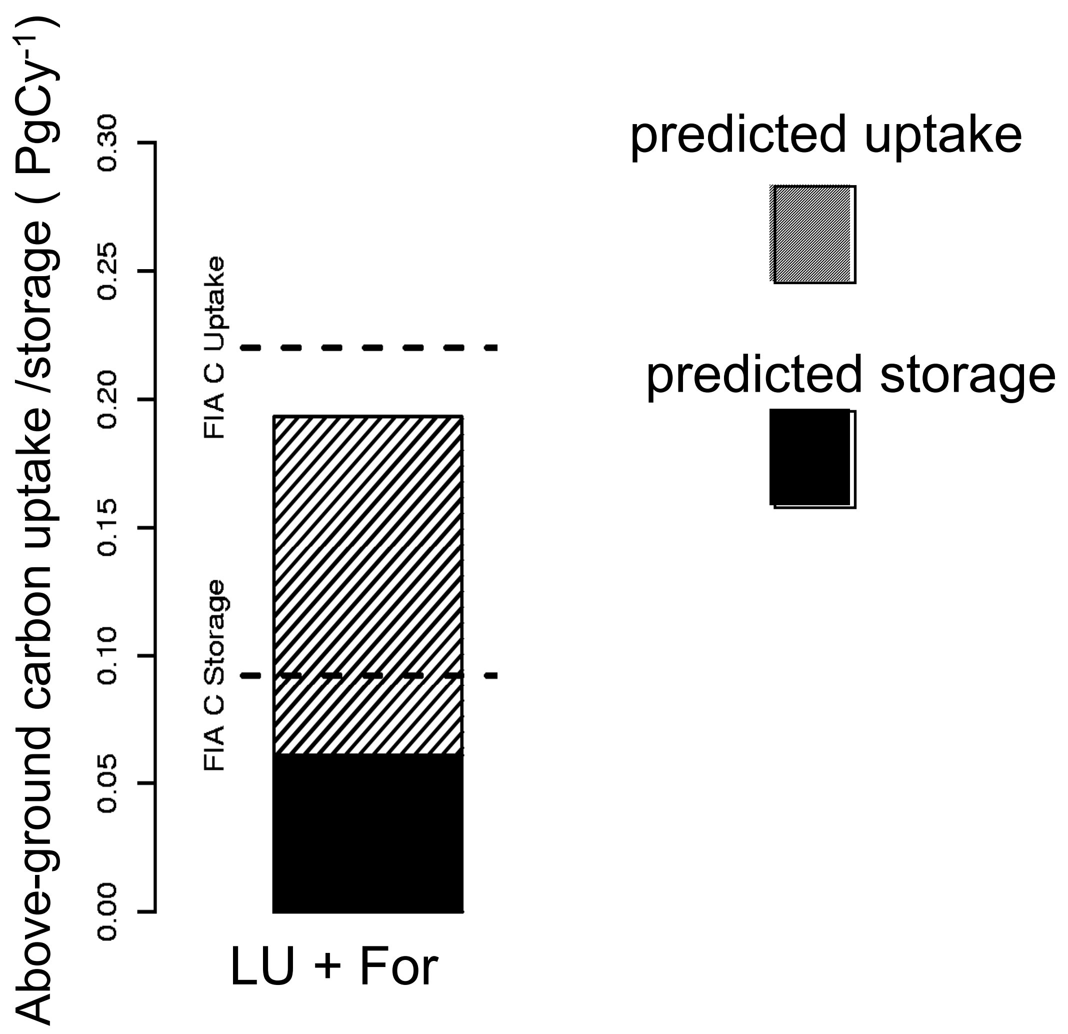




Albani et al. 2006



<- USFS FIA forest inventory measurements of current above-ground C uptake and storage

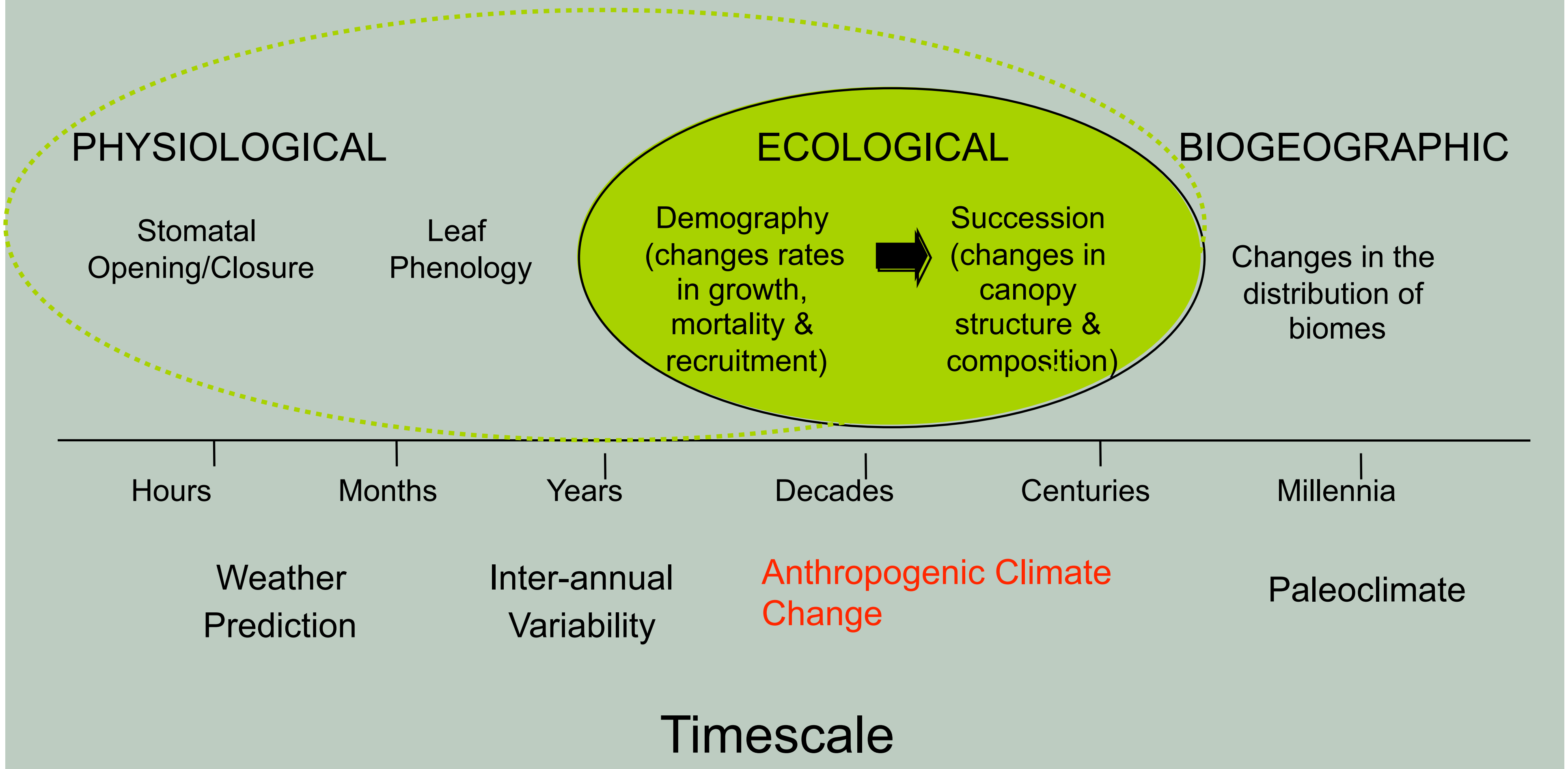


Results imply that:

- significant carbon uptake occurring as a result of land-use dynamics

- ~ 2/3 of the uptake is forest re-growth following harvesting, not carbon storage in forests.

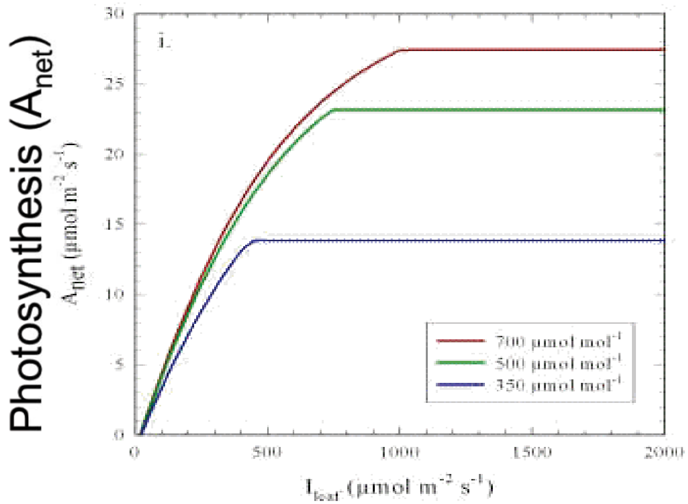
The physiological basis of plant demography

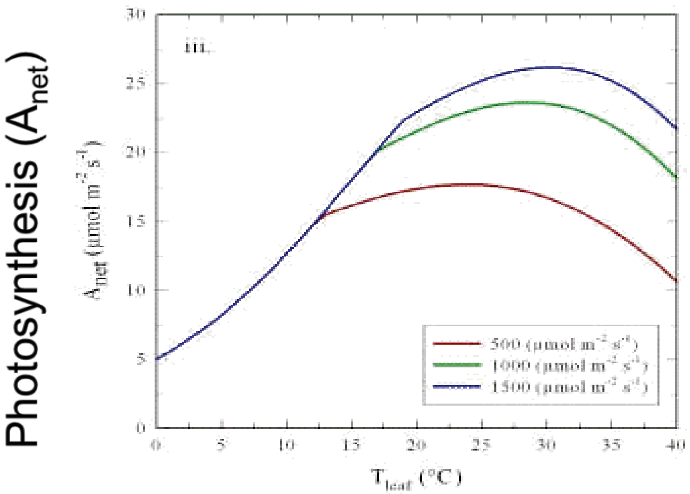


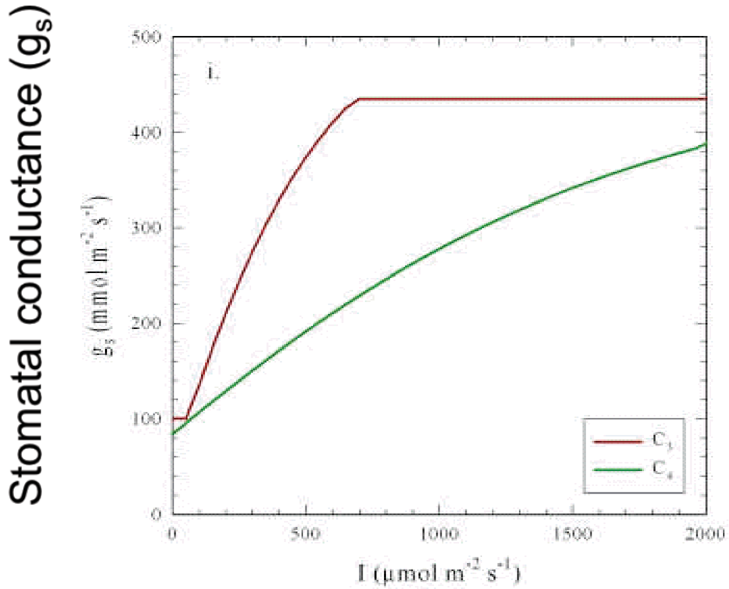
The Farquhar, Ball & Berry (Collatz et al.) model of photosynthesis

Inputs: (1) plant leaf traits; (2) environmental conditions: light, temperature, humidity, wind-speed and atmospheric CO_2 concentrations.

Outputs: the rate of carbon fixation (A_{net}) and evapotranspiration (ET) per unit leaf area





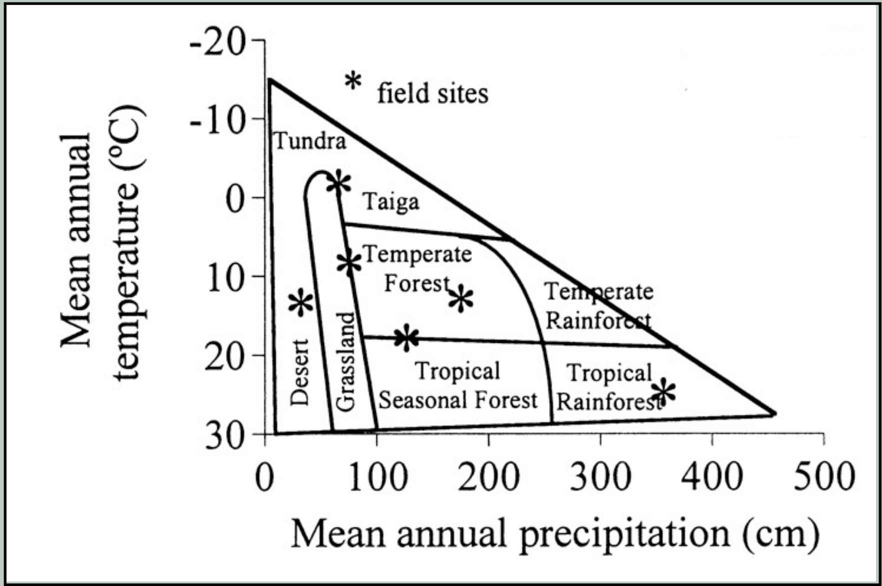


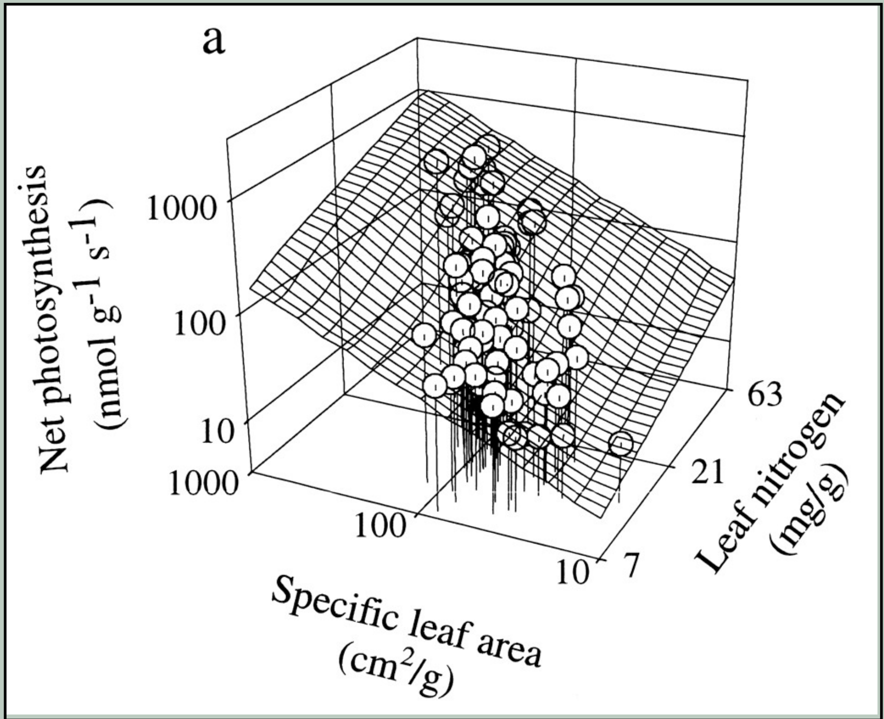
(ET is proportional to stomatal conductance (g_s))

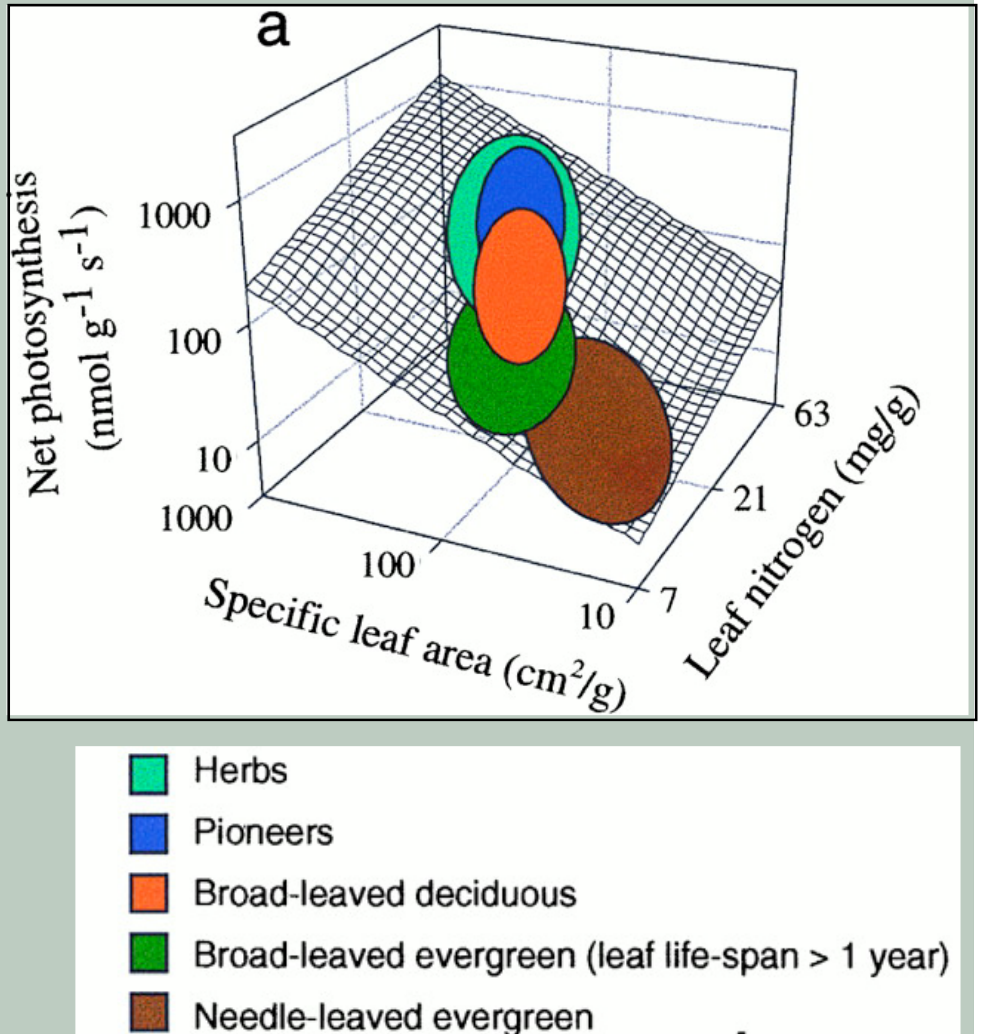
The effects of water availability are incorporated by solving the model equations under conditions of open and closed stomata, and then interpolating between the A_{net} and ET values obtained under the open stomata and closed stomata cases depending on the plant's water availability.

Leaf physiology of major plant functional groups

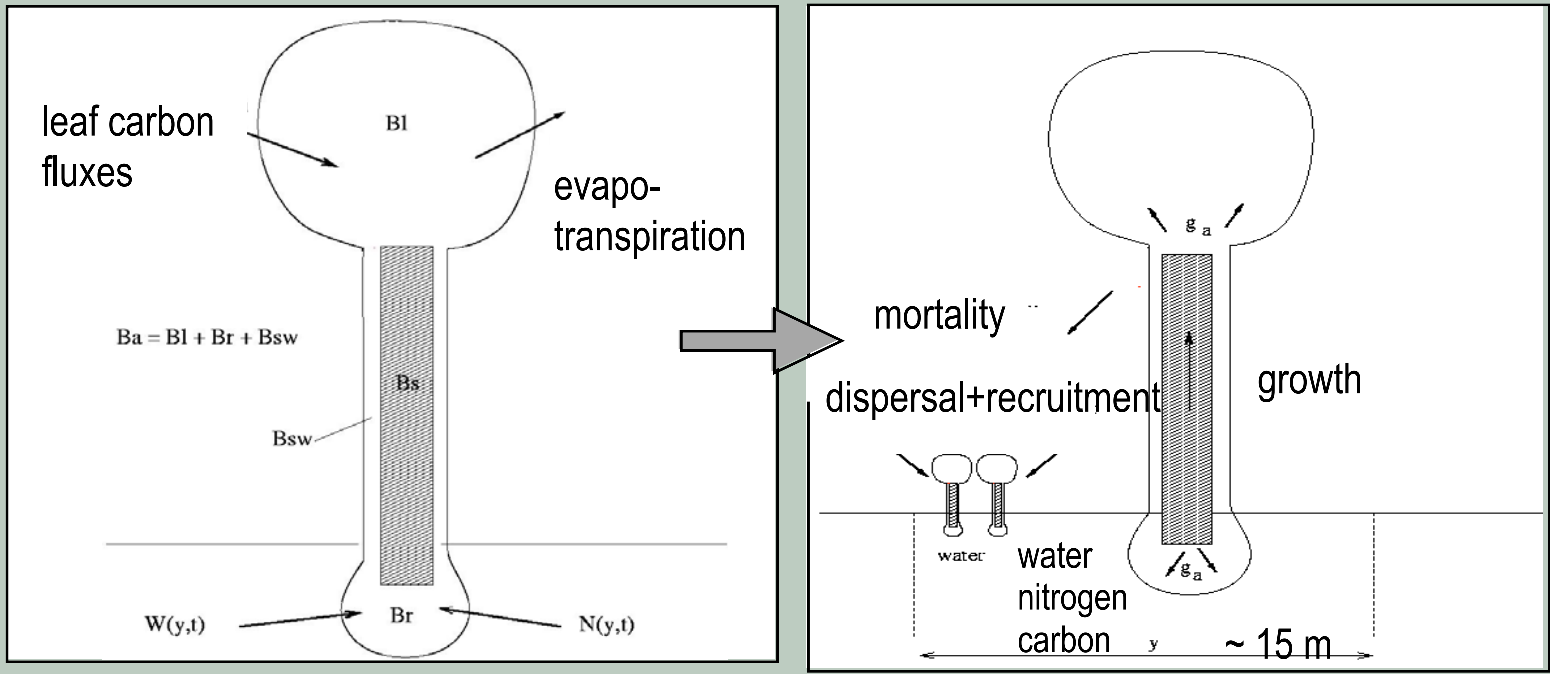
(Raich, Wright et al.)







Growth & Mortality

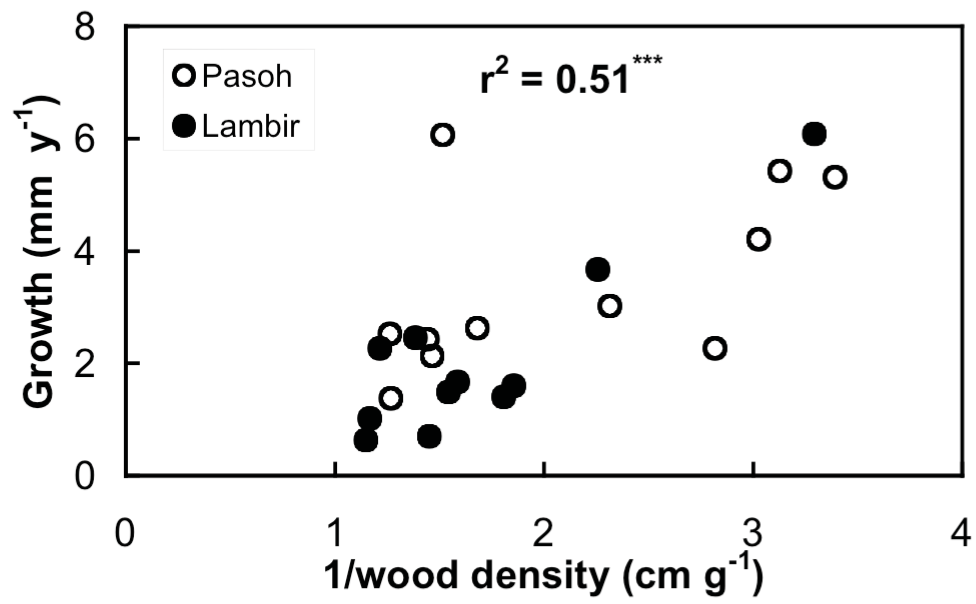


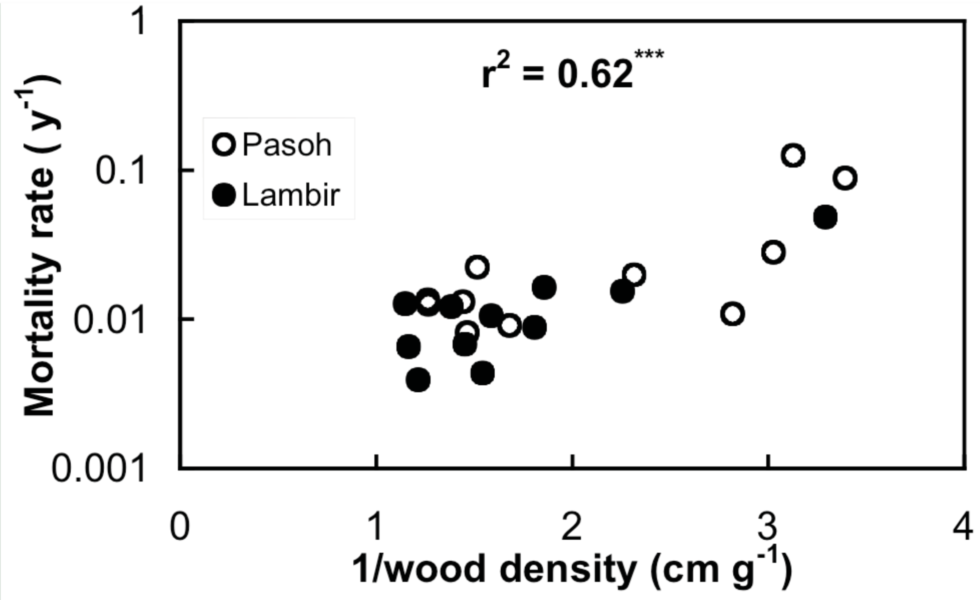
The plant has pattern of allocation, which determines how the carbon fixed by the plant is partitioned between growth of leaves, stems & roots, carbon storage, and seed production.

In conjunction with the plant's allometry (e.g. its height for a given stem biomass), the pattern of allocation determines the plant's size and rate of growth (height growth, diameter growth and root growth). These morphological characteristics determine its access to resources (light, water nitrogen).

The rate of mortality governed by the plant's carbon balance (carbon inputs minus losses from respiration leaf & root decay) as well as by is morphological characteristics.

Relationship between wood density and diameter growth rates and mortality rates for the 21 most abundant species present at 2 tropical forest sites in south-east Asia.

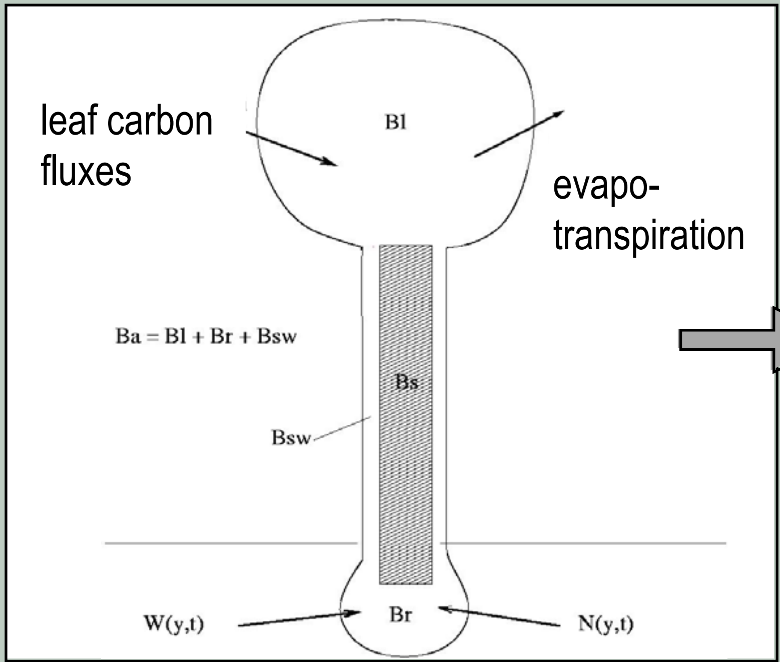


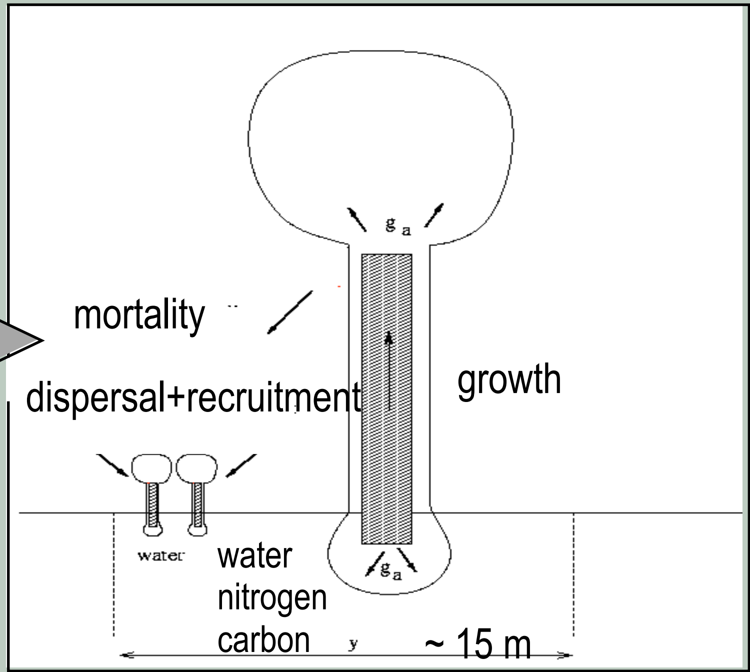


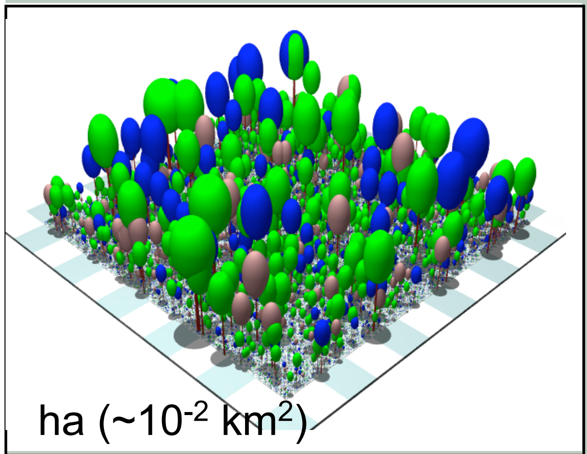
(King et al 2006)

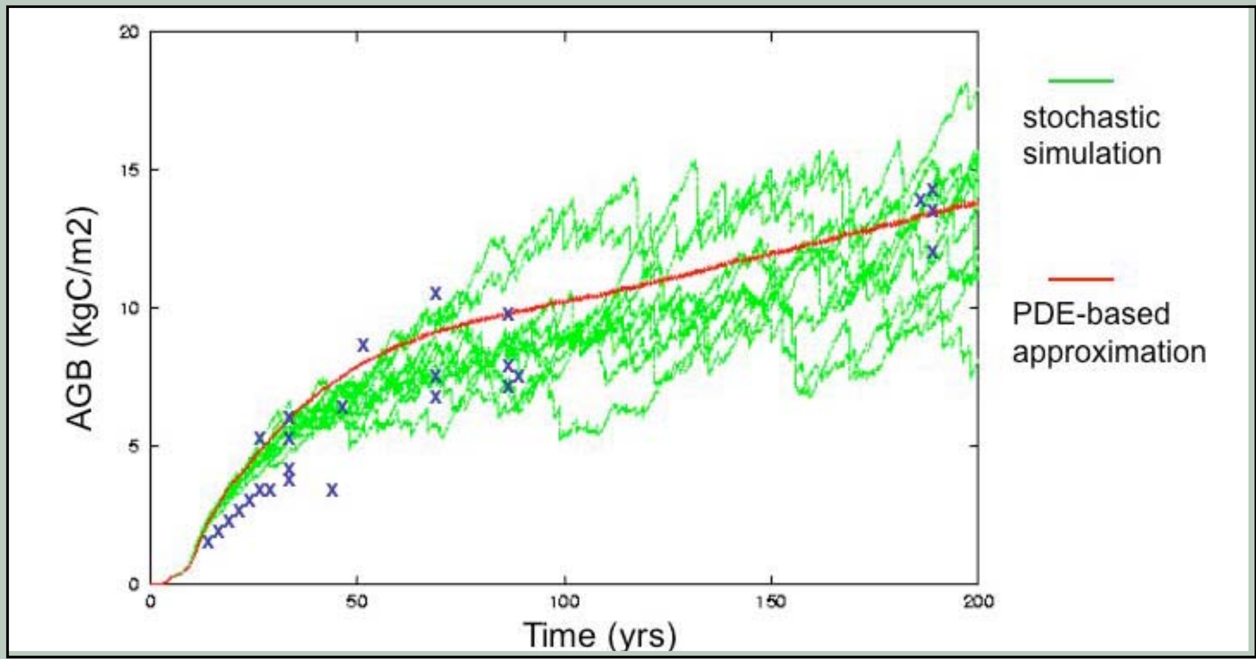
i.e. differences in wood density characterize a successional life history axis between pioneer species that have high rates of growth and adult mortality, and slower growing, longer-lived late successional tree species.

Individual-based vegetation models (gap models) *(Moorcroft et al. 2001)*









(Moorcroft et al. 2001, Moorcroft 2003)

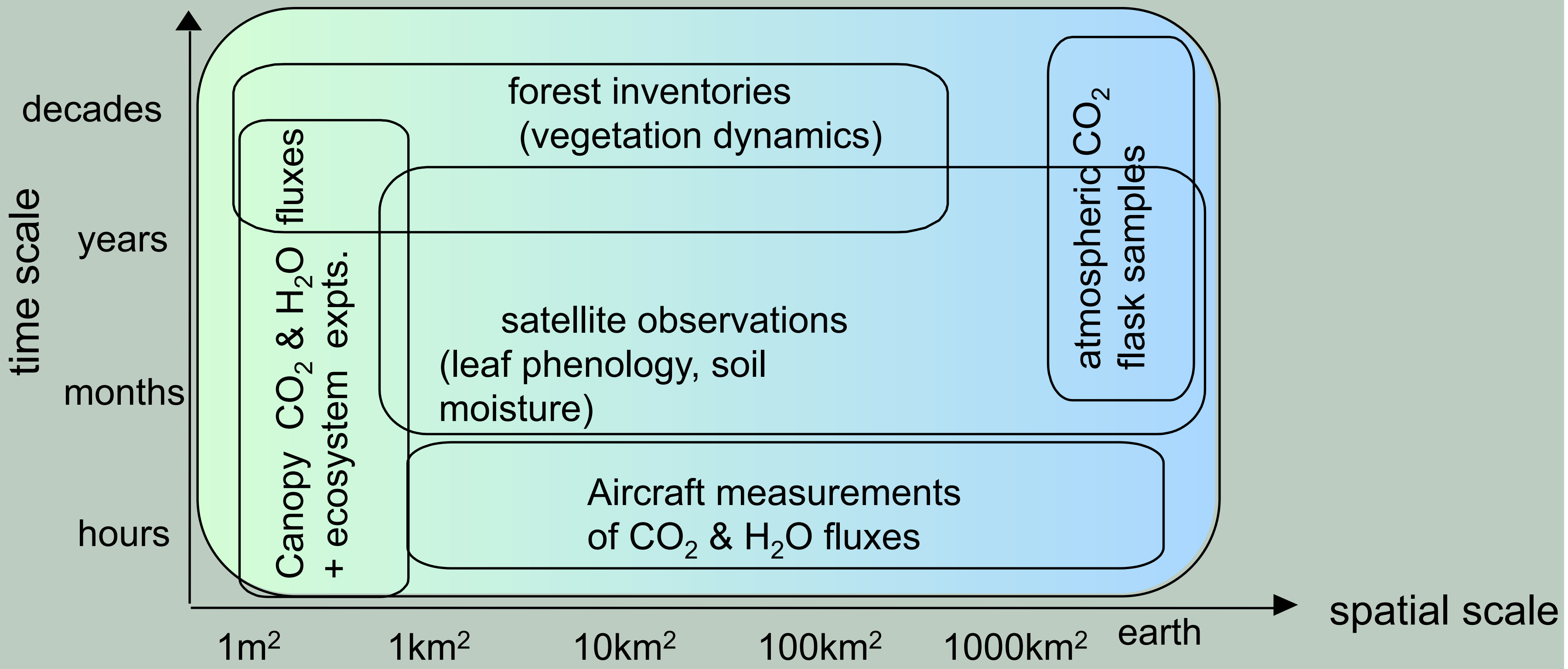
Question: How do we know that the underlying model formulation & parameters are correct?

Answer: evaluate the model against empirical measurements of ecosystem performance.

Linking terrestrial biosphere models to field measurements of ecosystem composition, structure & function

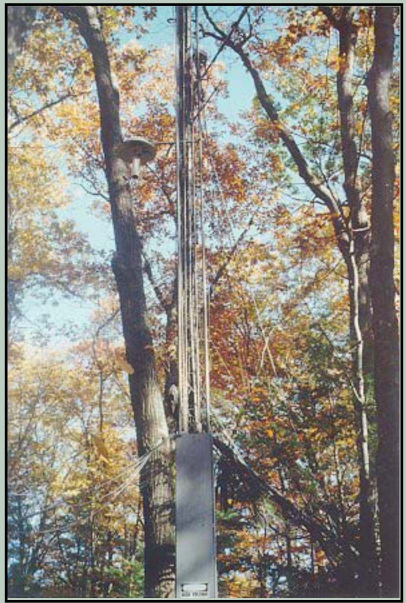
(Moorcroft Tnds Ecol. & Evol. 2006)

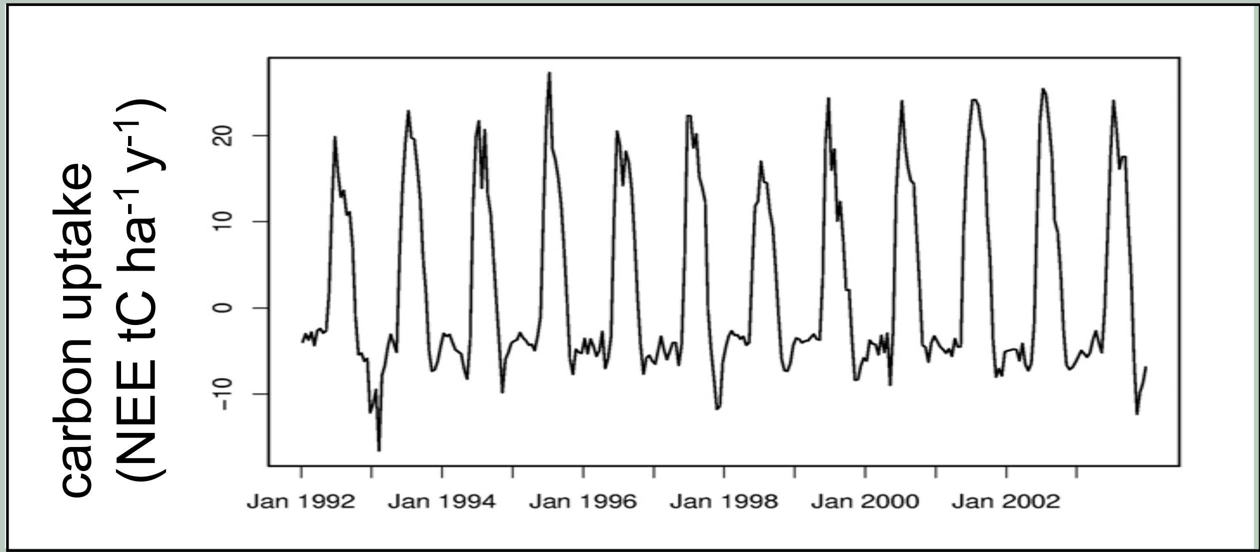
- models are fundamental to inference in global change biology because the predictions of interest are at scales larger than those at which most measurements are made.

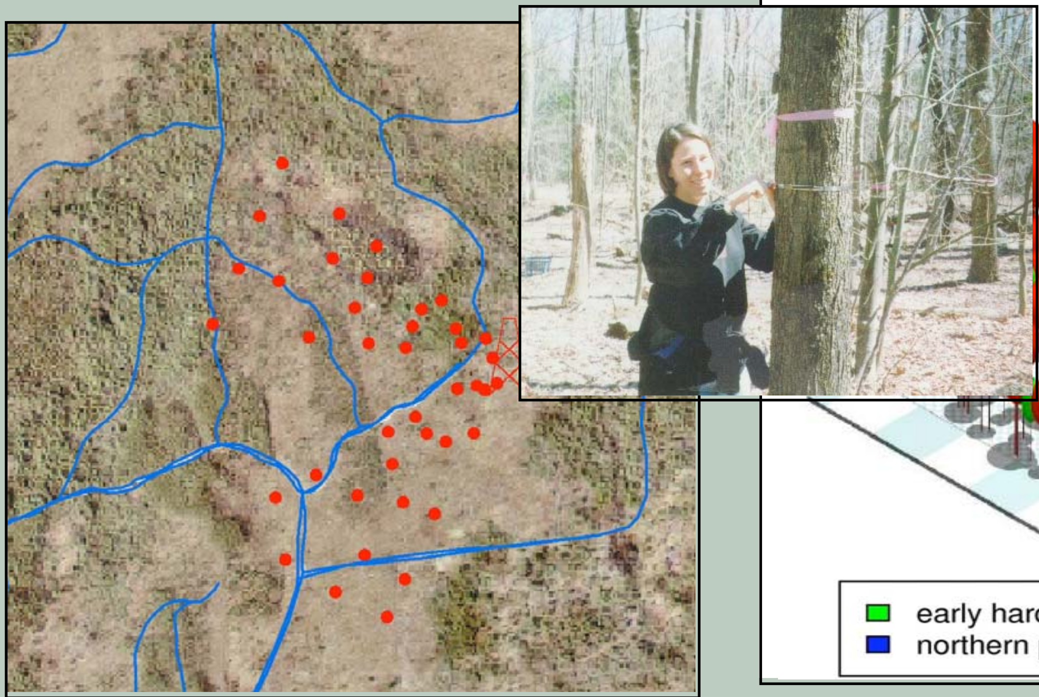


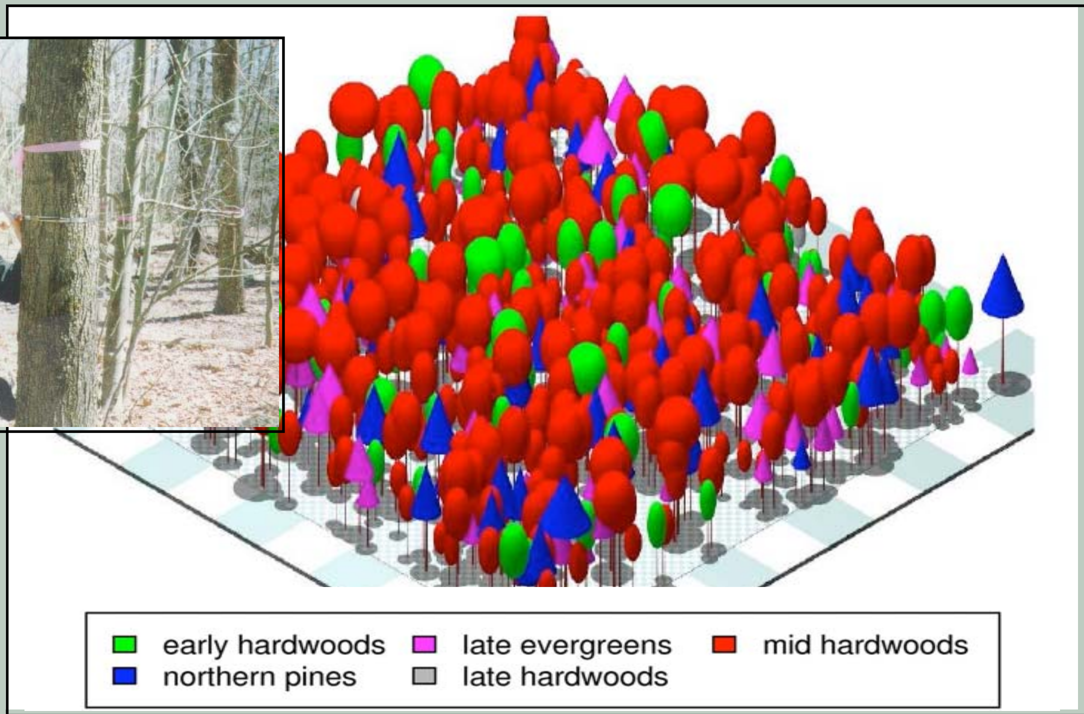
- as a result, scaling is a key issue

Harvard Forest LTER ecosystem measurements







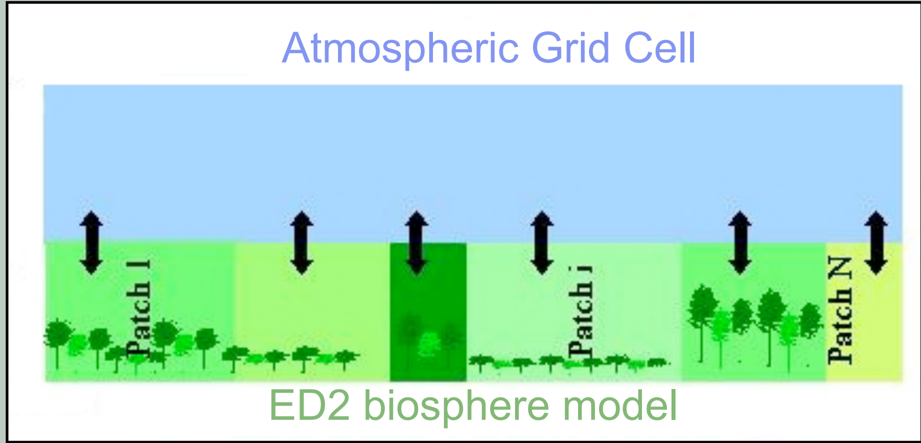


ED2 model fitting at Harvard Forest (42°N, -72°W)

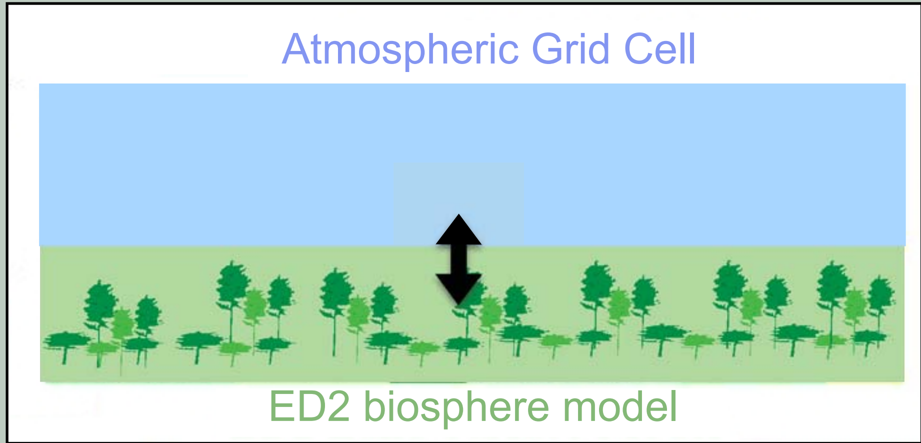
Initial model: traditional approach in which model parameters are specified from literature values.

2 optimized model formulations:

HET: horizontal heterogeneity in canopy structure is explicitly represented



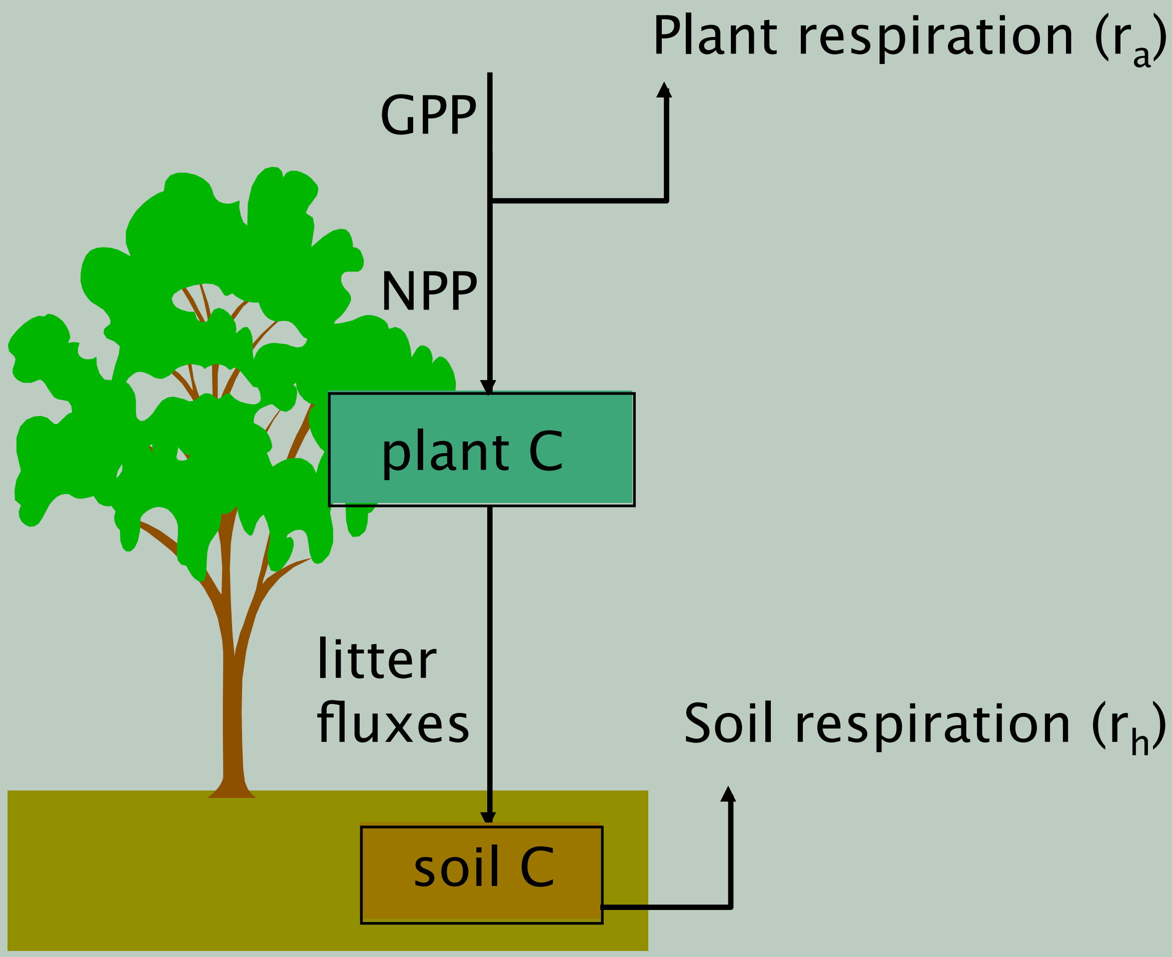
AGG: a horizontally-averaged. 'big-leaf' representation of canopy structure.



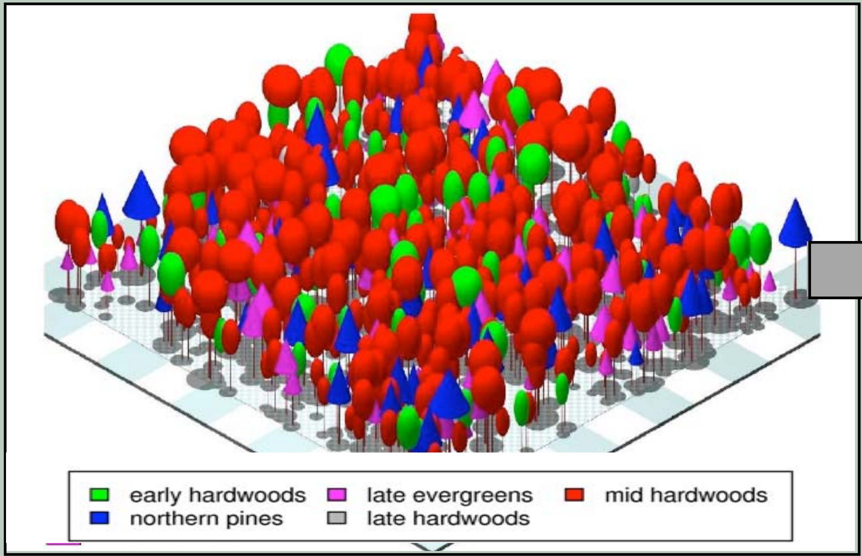
> Can we demonstrate that the ED model's ability to represent fine-scale ecosystem heterogeneity improve its ability to predict long-term, large-scale ecosystem dynamics?

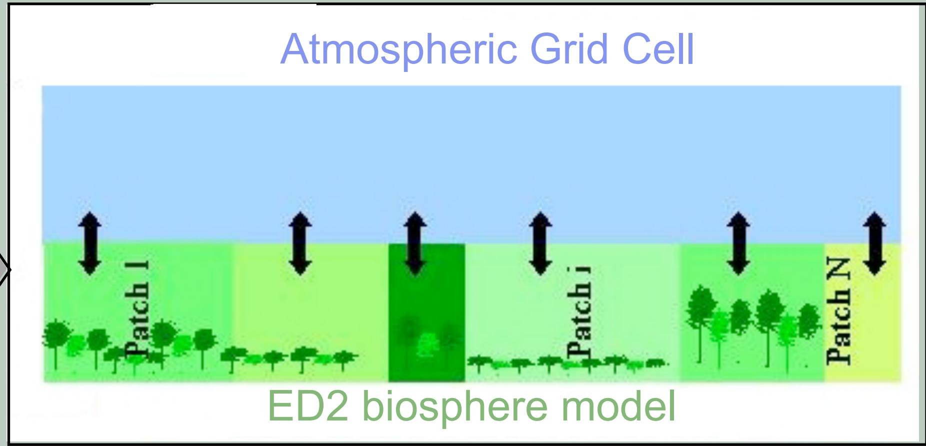
Net Carbon Uptake (NEP)

$$NEP = GPP - (r_a + r_h)$$



Methodology

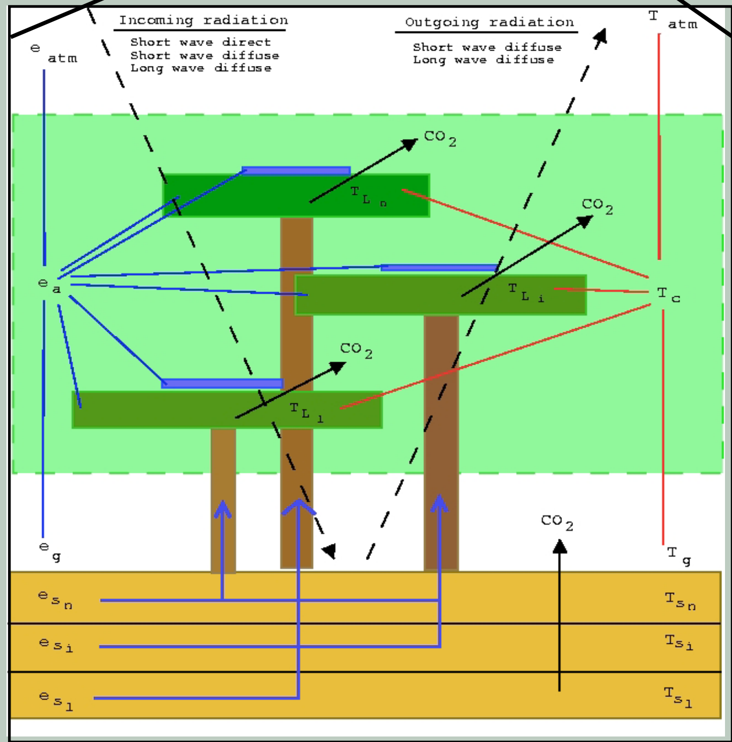




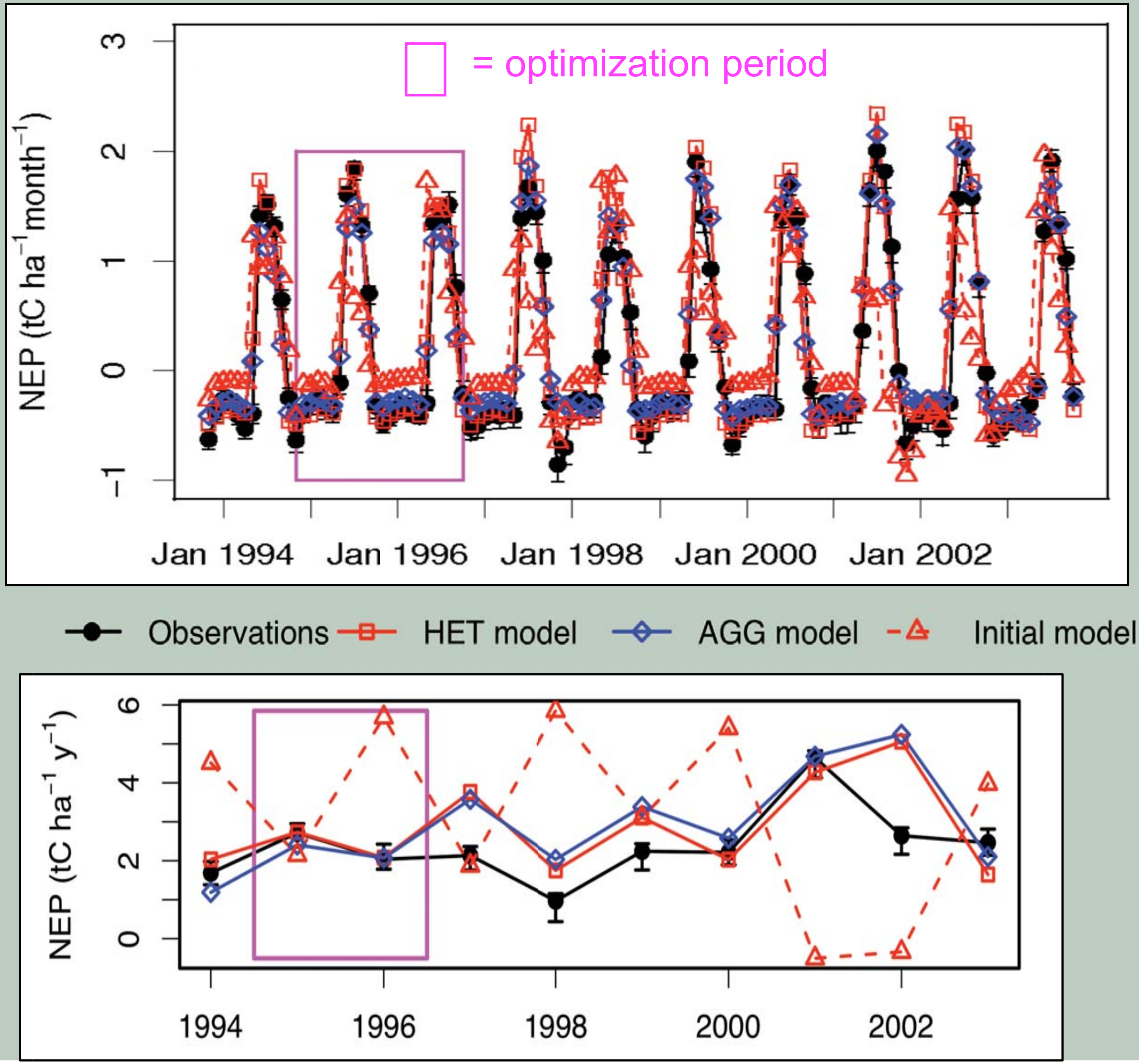
- initialize with observed stand structure & force with observed climate & radiation data

- 2 year model fit (1995 & 1996), in which model constrained against:
  - hourly, monthly & yearly daytime and night-time NEP, hourly ET
  - growth & mortality rates of the trees in the flux tower footprint

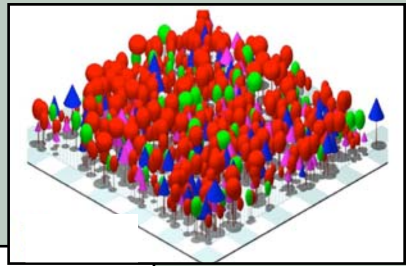
- also performed a separate analysis that constrained the timing of leaf onset & offset.



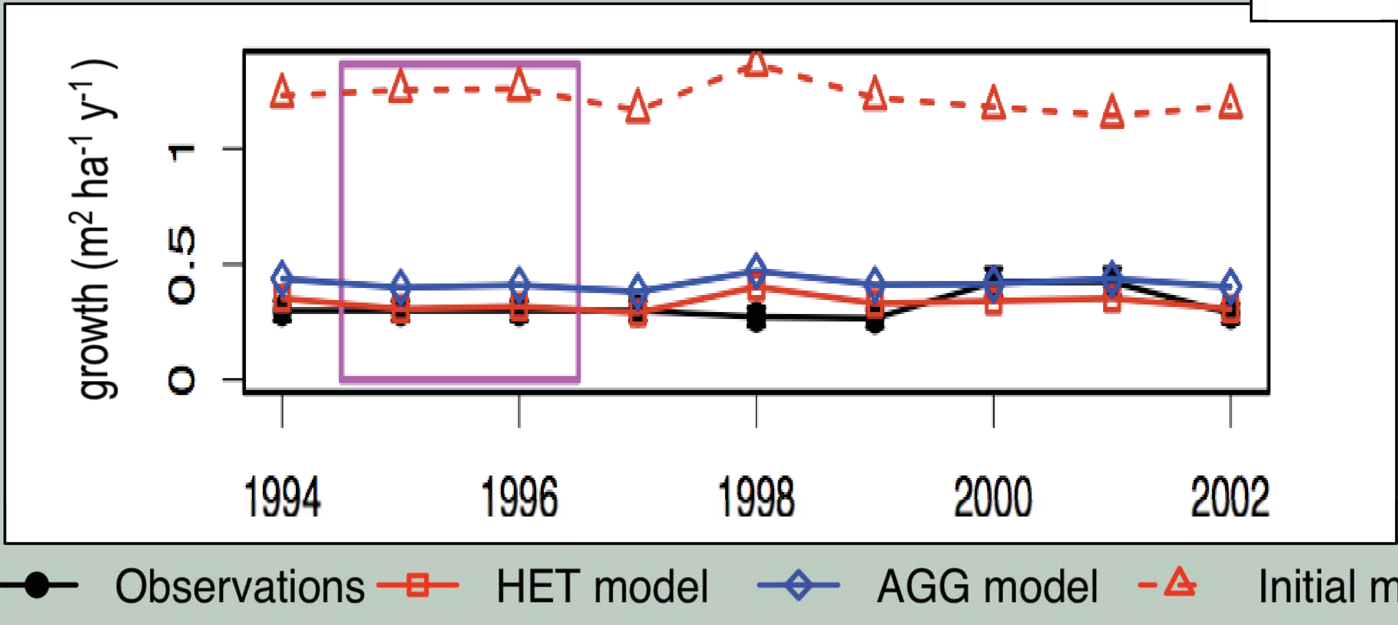
Improved predictability at Harvard Forest: 10-yr simulations (1992-2001)



Improved predictability at Harvard Forest:
10-yr patterns of growth and mortality (1992-2001)

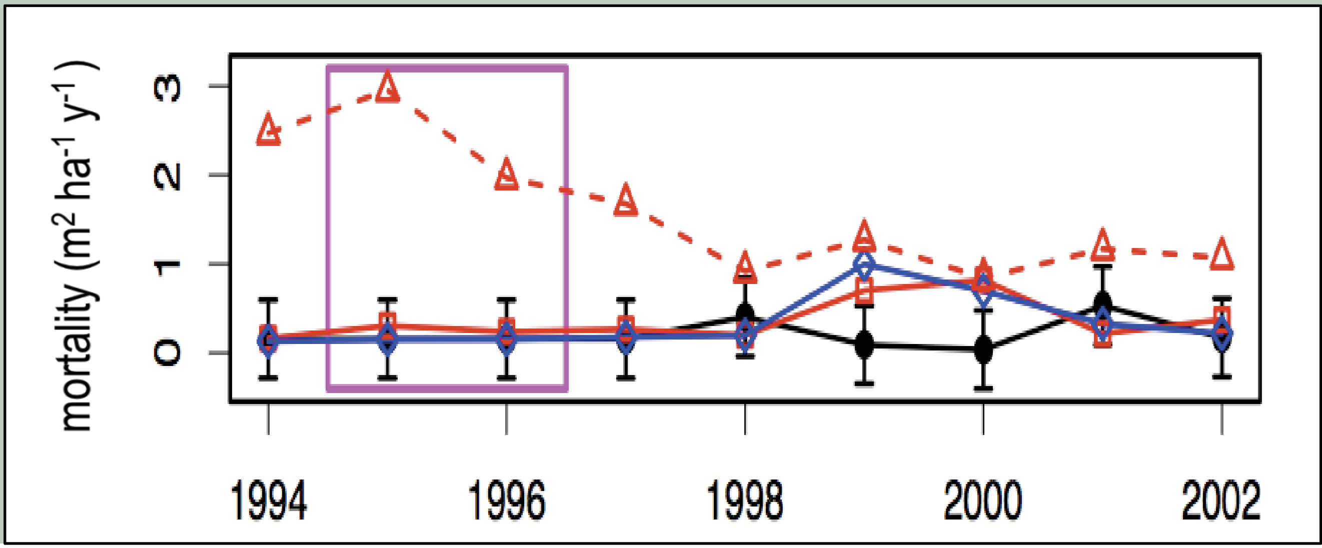


tree growth:

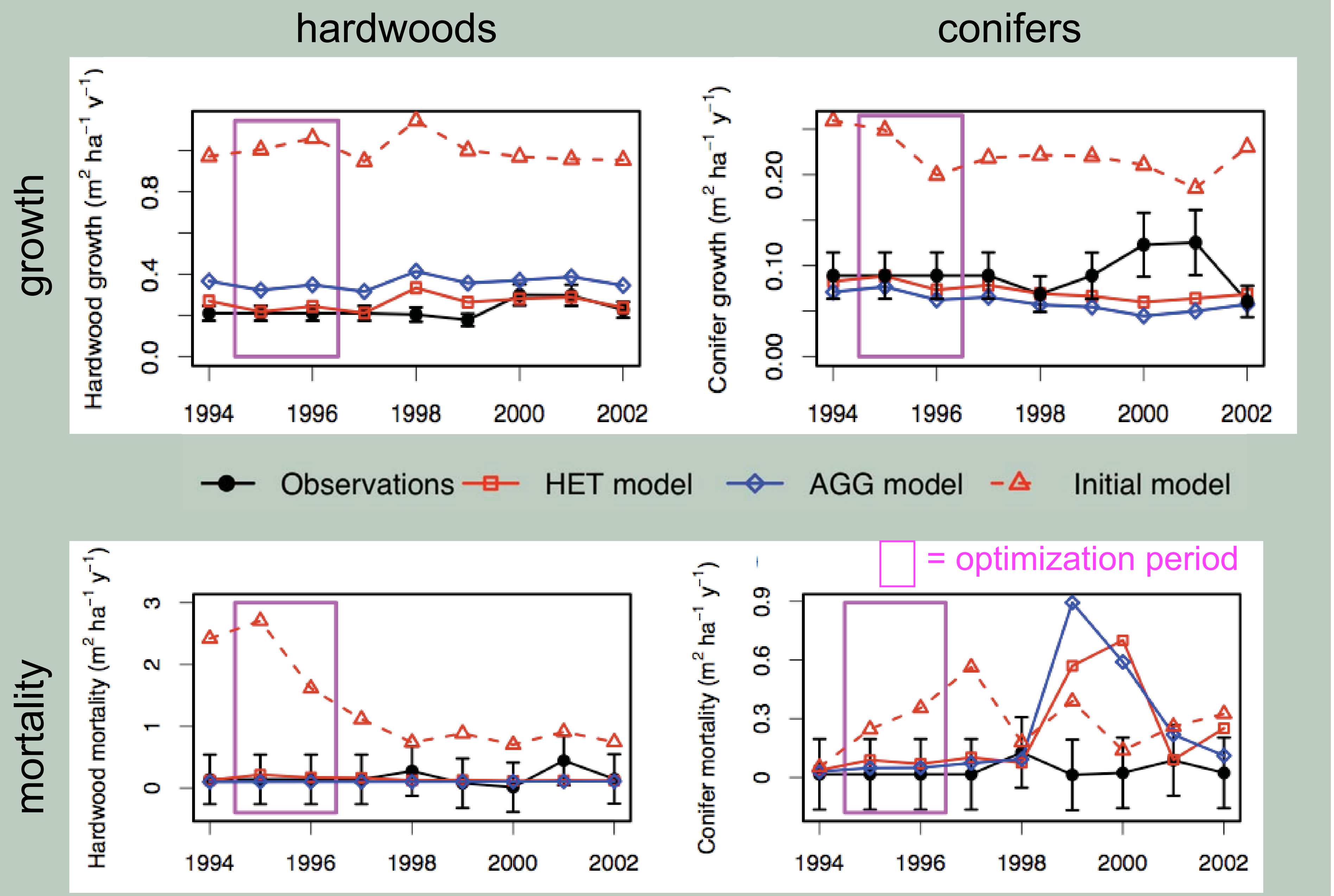


= optimization period

tree mortality:



Improved predictability at Harvard Forest: 10-yr simulations (1992-2001)



Vegetation model optimization: results

Change in goodness of fit: 450 log-likelihood (Δl) units (sig level: Δl= 20)

Parameter	Symbol	Initial value	Optimized value and 2σ uncertainty, HET	Optimized value and 2σ uncertainty, AGG
Stomatal Slope	M	8	6.4 (1.3)	6 (6)
Hardwood V_{m0} multiplier	$V_{mult,hw}$	1	1.1 (0.08)	0.71 (0.20)
Conifer V_{m0} multiplier	$V_{mult,co}$	1	0.73 (0.10)	0.76 (0.38)
Photosynthesis temperature threshold (°C)	$T_{V,lo}$	5	4.7 (2.3)	5 (7)
Fine root turnover rate (y^{-1})	α_{root}	0.333	5.1 (0.5)	2.0 (0.9)
Allocation to fine roots relative to leaves, hardwoods	q_{hw}	1	1.1 (0.2)	1.4 (1.3)
Allocation to fine roots relative to leaves, conifers	q_{co}	1	0.35 (0.07)	0.8 (0.5)
Water availability parameter (m^2 y^{-1} (kgC root)$^{-1}$)	K_W	160	150 (-23, +1200)	170 (92)
Conifer growth respiration fraction	$r_{g,co}$	0.333	0.45 (0.06)	0.35 (0.17)
Hardwood growth respiration fraction	$r_{g,hw}$	0.333	-	-
Hardwood storage respiration rate (y^{-1})	$\alpha_{storage,hw}$	-	0.62 (0.08)	0.49 (0.16)

HET model parameters have lower uncertainties than the AGG model parameters

Soil decomposition model

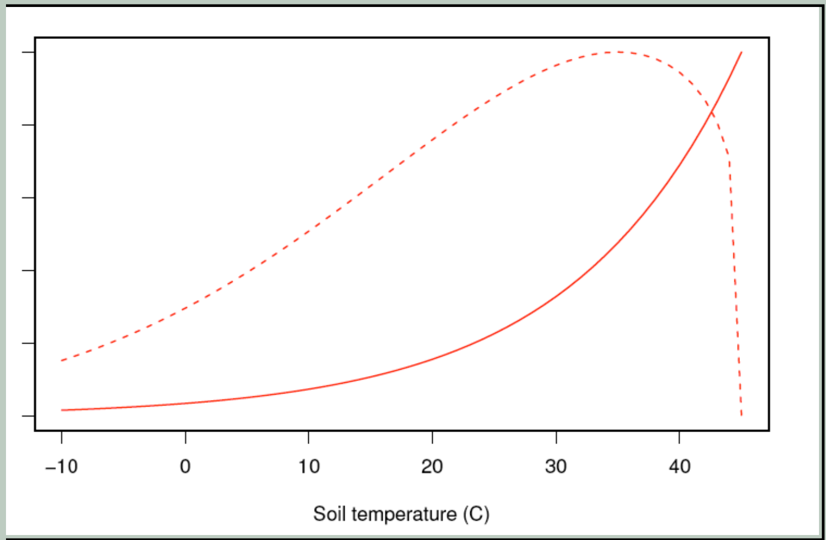
3-box biogeochemistry model
(fast, structural & slow C pools)

initial

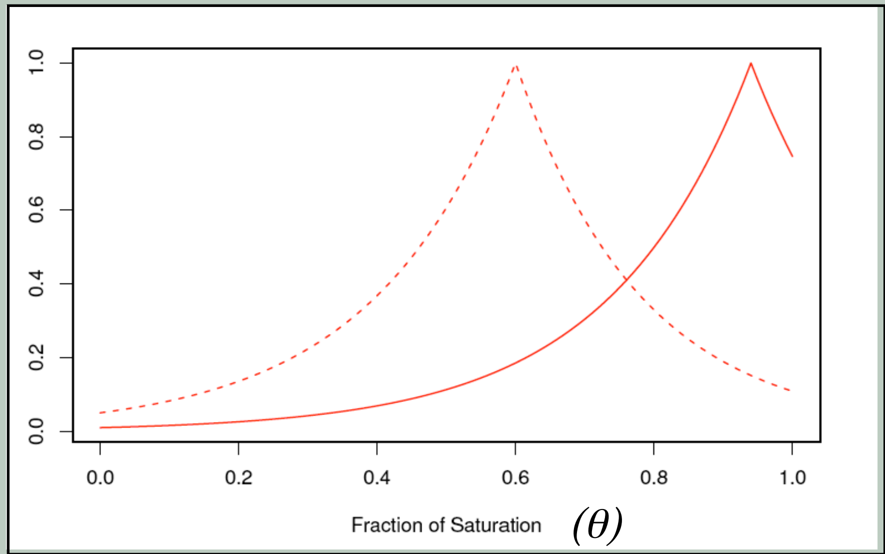
HET

relative decomposition rate

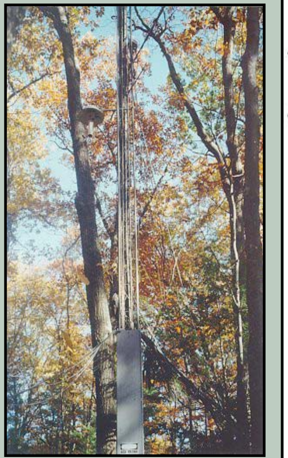
temperature sensitivity $f(T)$

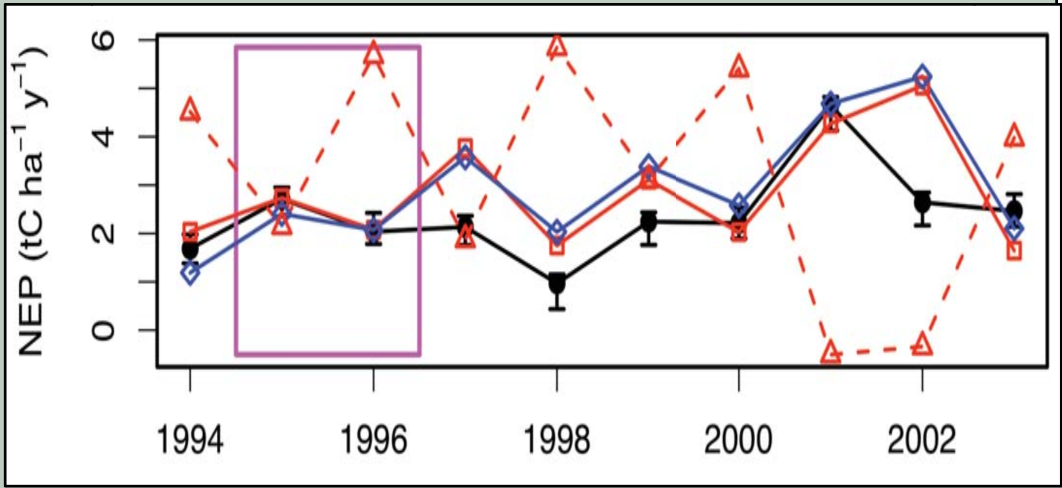


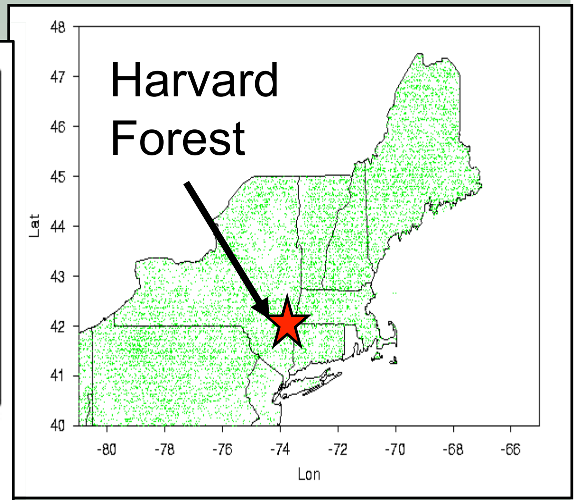
soil moisture sensitivity $f(\theta)$

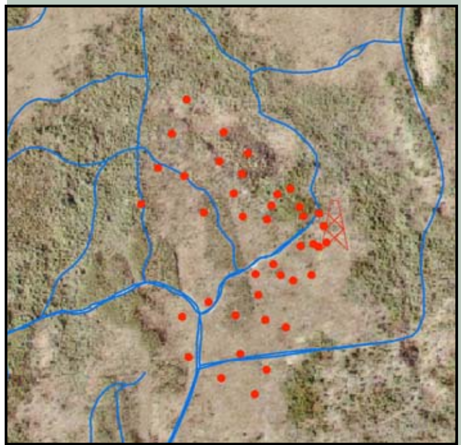


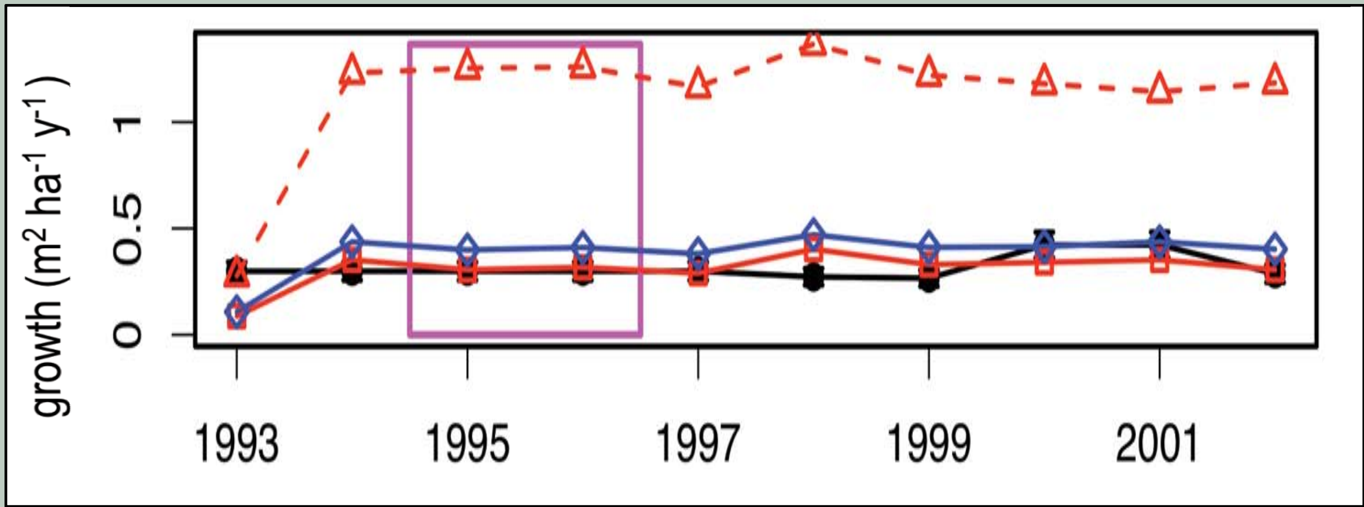
Summary: Harvard Forest: 10-yr simulations (1992-2001)





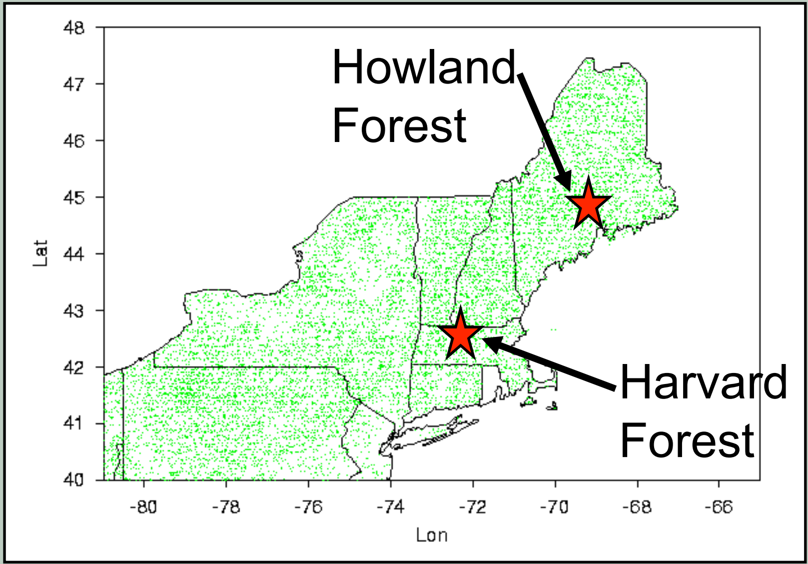


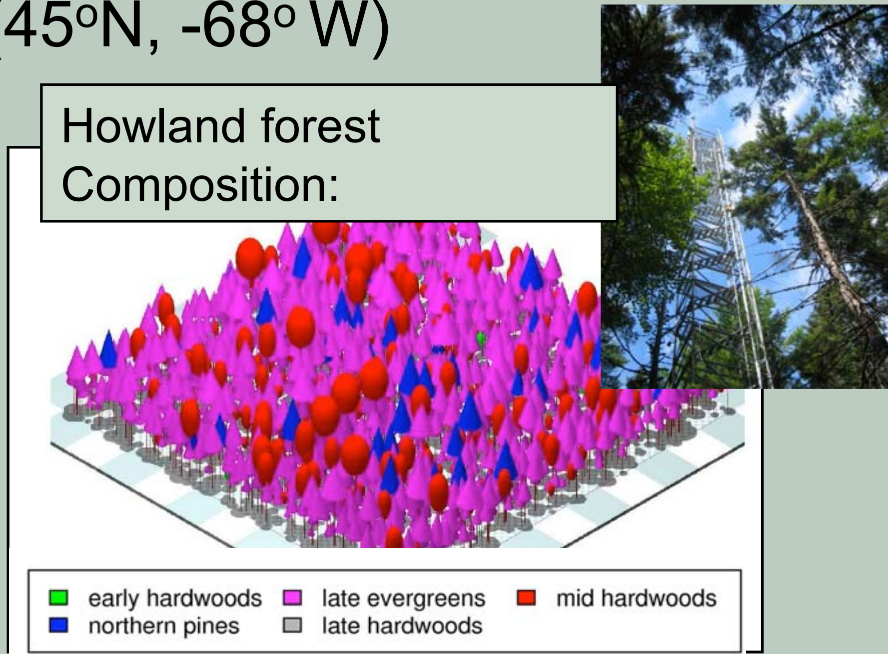




Demonstrated improved predictability in time. But what about in space?

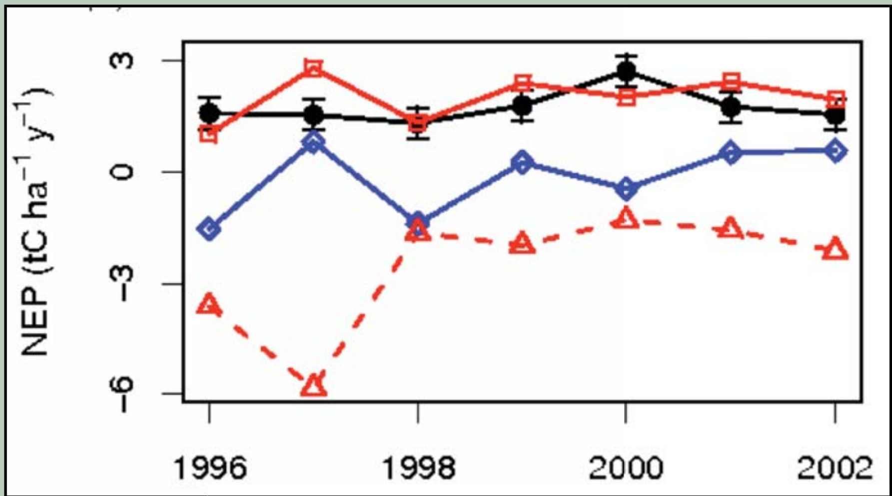
Howland Forest (45°N, -68° W)



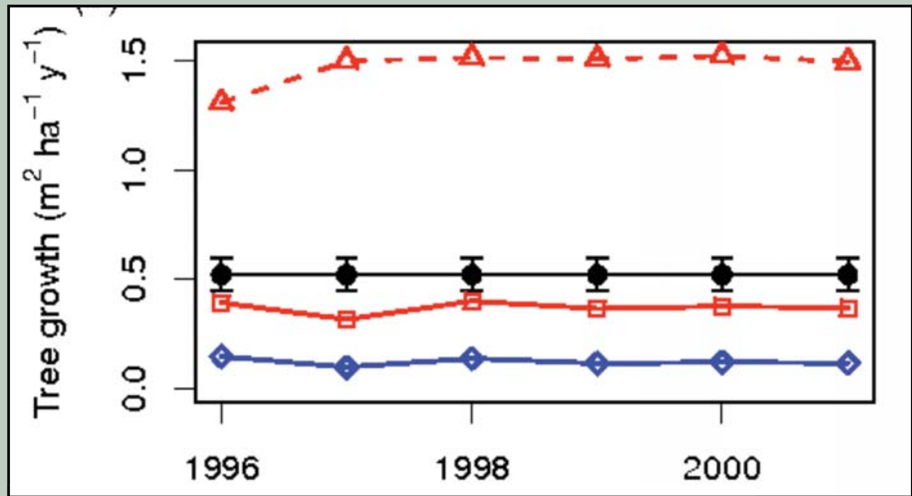


(no changes in any of the model parameters)

net carbon fluxes (NEP)



tree growth

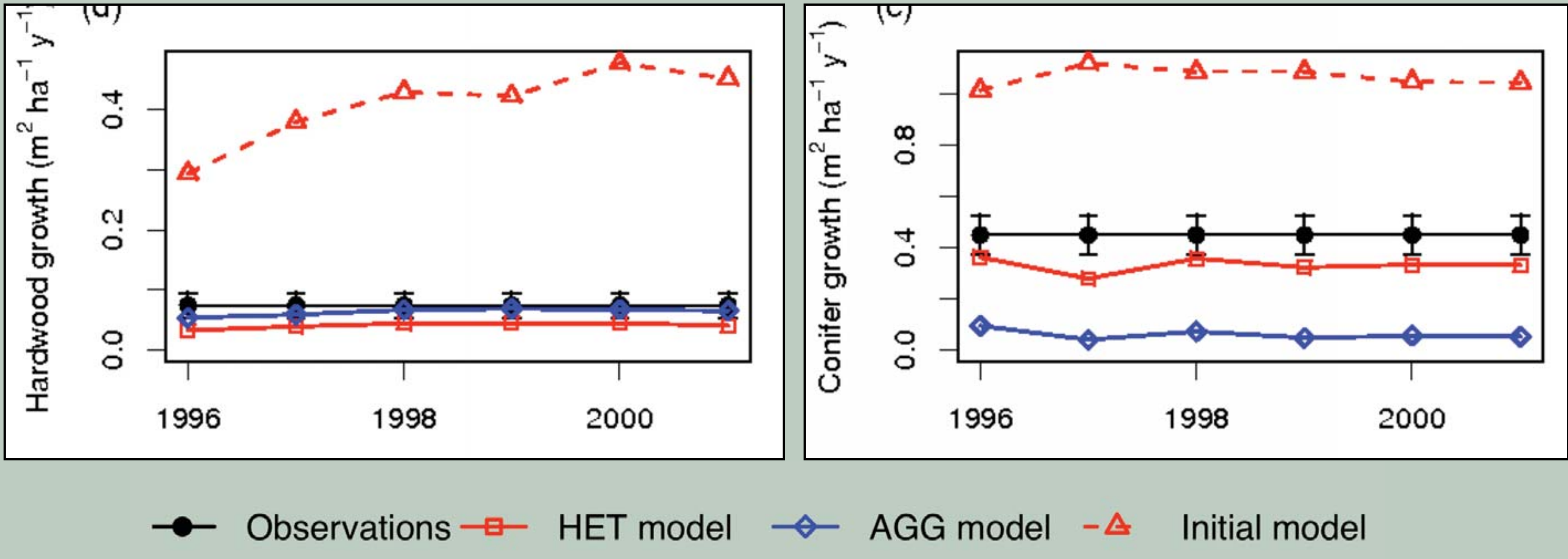


Observations HET model AGG model Initial model

Improved predictability at Howland Forest: 5-yr simulations (1996-2000)

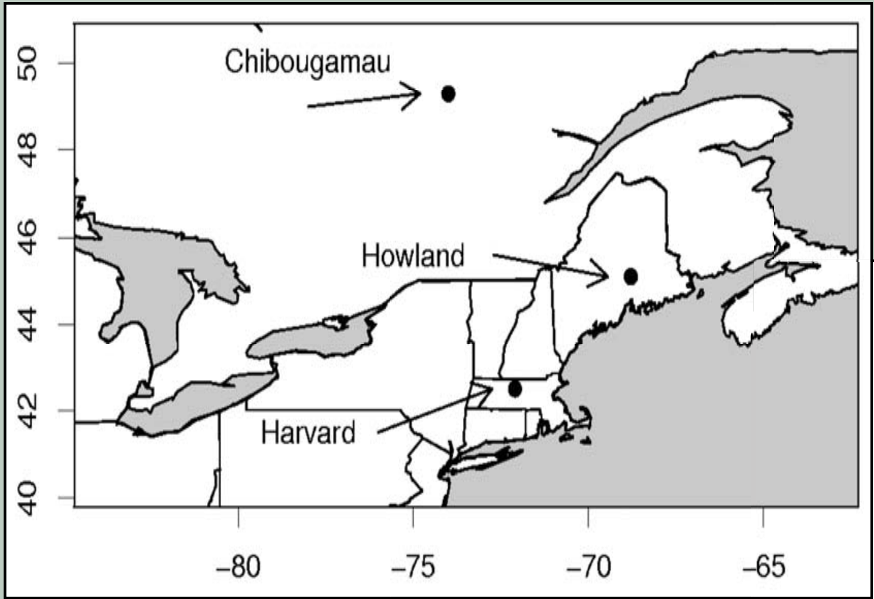
hardwood basal area increment (tC ha^{-1} mo^{-1})

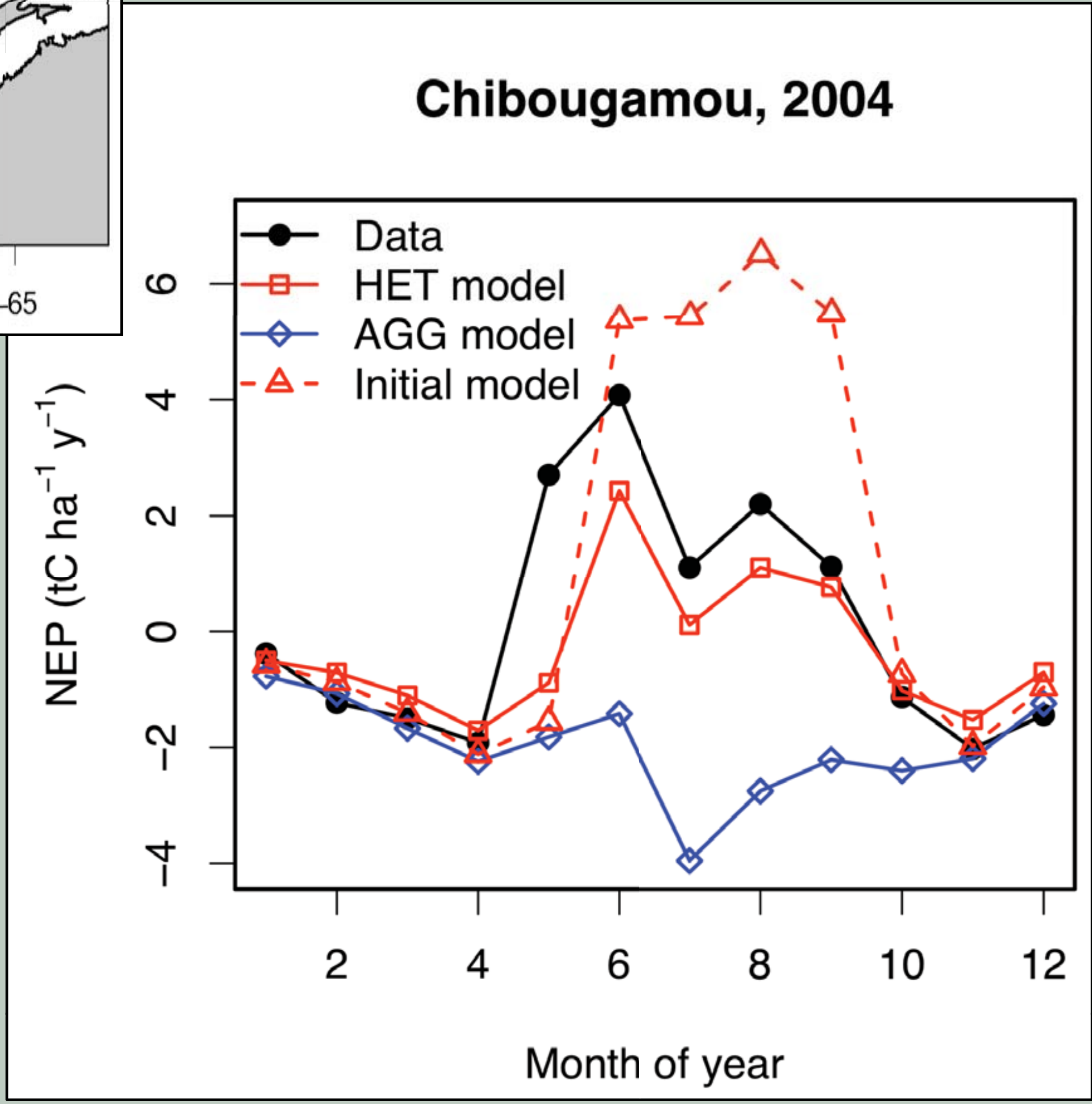
conifer basal area increment (tC ha^{-1} mo^{-1})



=> model improvements are general, not site-specific

=> HET model outperforms AGG model


Chibougamau
Howland
Harvard
50
48
46
44
42
40
−80
−75
−70
−65


Chibougamou, 2004
Data
HET model
AGG model
Initial model
NEP (tC ha−1 y−1)
6
4
2
0
−2
−4
2
4
6
8
10
12
Month of year

Conclusions

How close are we to a predictive science of the biosphere?

Structured biosphere models such as ED2 can be parameterized & tested against field measurements yielding a model with accurate:

- canopy-scale carbon & water fluxes
- tree-level growth & mortality dynamics

Demonstrated that incorporating of fine scale ecosystem heterogeneity yields:

- improved ability to capture short-term & long-term vegetation dynamics (i.e. scale accurately in time).

- improved ability to capture regional scale variation in ecosystem dynamics without the need for site-specific parameters or tuning (i.e. scale accurately in space).

Shown that it is possible to develop terrestrial biosphere models that not only make predictions about the future of ecosystems, but are also truly predictive.